ASSESSING CONSTRUCTED WETLANDS FOR BENEFICIAL USE OF SALINE-SODIC WATER

by

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ABSTRACT

Changes in agricultural practices, and irrigation strategies combined with natural processes, have led to increased salinization of soil and water resources worldwide. Coal bed methane (CBM) development in the Powder River Basin of Montana and Wyoming results in the co-production of large volumes of sodic and moderately saline discharge water, and represents a potential source of salinization of soil and water resources.

The objective of this study was to evaluate the potential of constructed wetlands as a tool for CBM product water management. This was accomplished by assessing seasonal water use, biomass production and water use efficiencies (WUE) of three plant communities. Native species establish hydrologically distinct communities in former ephemeral channels now running with CBM product water, and nine species of those cataloged were selected and segregated into three communities. Closed-system wetland cells were constructed and each community was assigned to four of these cells, i.e., lysimeters. Chemistry of the supply water was sodic and moderately saline (EC ~ 3.4 dS/m, SAR > 25), typical of northern portions of the Powder River Basin where low to moderate electrical conductivities (EC 2-3 dS/m) and high sodium adsorption ratios (SAR > 20) are common.

All three communities had similar total water use but WUE's differed significantly among the communities. Evaporation from a Class A evaporation pan was observed to be higher than evapotranspiration from the planted lysimeters, but this is not definitive as there was only one replication of the pan.

Species survival and colonization was very good for seven of the nine species selected. American bulrush (*Scirpus americanus*) had very sparse spring regrowth and Inland saltgrass (*Distichlis stricta*) was likely out-competed by Creeping spikerush (*Eleocharis palustris*).

Results of this study indicate that constructed wetlands planted with native, salt tolerant species have potential to utilize substantial volumes of CBM product water while remaining robust and viable. Although results suggest evaporation from an open water surface to be greater than evapotranspiration from a constructed wetland, constructed wetlands have added benefits of providing wildlife habitat, recreation and viewshed enhancement.

INTRODUCTION

Background

The Powder River Basin is a geologic basin located in northeast Wyoming and southeast Montana. Irrigators along the Tongue and Powder Rivers in Montana receive their irrigation waters from the Powder River Basin. Geologically, the basin is a source of salinity for in-channel water (Van Voast, 2003). Another potential source of salinity is waste water from oil and gas production, which may be high in sodium and may alter physical and chemical properties of soils (Robinson, 2002). Under specific circumstances sodium has the potential to induce soil surface crusting, inhibit germination and seedling establishment, reduce water infiltration and soil hydraulic conductivity, as well as increase runoff and soil erosion (Miller and Donahue, 1990; Brady and Weil, 1999; Or et al., 2002). Discharge of water with increased salinity, especially sodium, in areas already high in geologically derived sodium, may cause a wide range of plant effects, from lower yields to plant mortality (Hanson et al., 1999). Technologies and best management practices for addressing the issue of large volumes of sodic and moderately saline water are in high demand and will be critical to sustain compatibility of mineral extraction and traditional land and water resource uses in the basin.

Presence of extensive coal deposits with significant storage of natural gas in Wyoming, Colorado, Utah, and Montana have stimulated coalbed methane (CBM) extraction and recovery in these states over the last ten years. Predictions point to the

Powder River Basin of Wyoming and Montana as the next significant area of development (Northern Plains Resource Council, 2001; De Bruin et al., 2002). The basin is, geographically, the largest of the CBM producing basins in the western U.S. (Van Voast, 2003) (Figure 1).

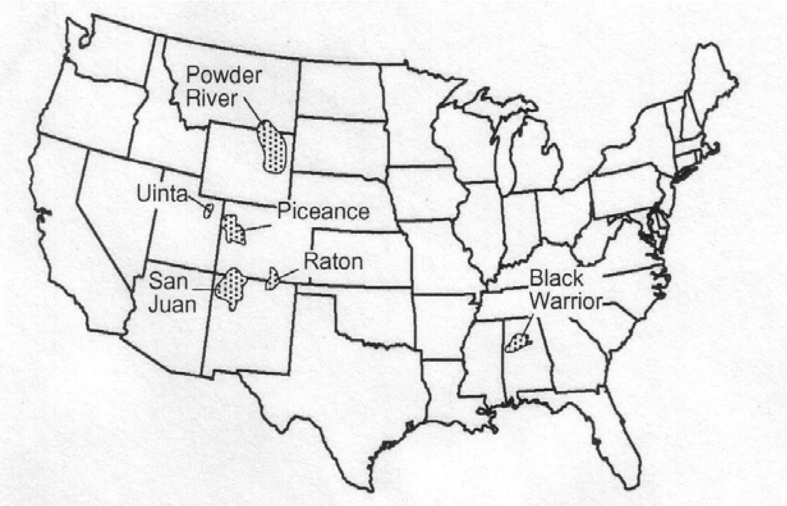

Figure 1. Principal CBM producing regions in the U.S. 2001. From Van Voast, 2003.

Coal deposits that contain methane gas in the Powder River Basin occur at relatively shallow depths, making methane recovery economical. Shallow coal deposits are only one of the reasons CBM recovery is more economical than traditional extraction of coal and oil. Others include lower exploration costs and more cost-effective drilling (Robinson, 2001). Coal bed methane or natural gas, when burned properly, is a cleaner fuel which emits, on average, half the carbon dioxide (CO_2) of coal, with fewer particulates (Flores, 1998; McMillion, 2000).

CBM and natural gas are both methane (CH_4) that forms when plant material is turned into coal by the geologic process of coalification. The main difference between

CBM and natural gas is that CBM is trapped and held within saturated or submerged coal seams by hydrostatic pressure (Flores, 1998; De Bruin et al., 2002). There are three ways in which methane is trapped in coal seams. The first is adsorption on the molecular structure of the coal or other material surfaces. Methane can also be a free gas trapped within micropores and surface cracks of coal seams, or a dissolved gas within water.

Extraction of methane involves pumping water from coal seams to reduce hydrostatic pressure, which promotes desorption and frees methane for capture in a pipeline (Figure 2). As a result of this process, significant quantities of water containing dissolved solids, particularly sodium, are brought to the surface and must be managed.

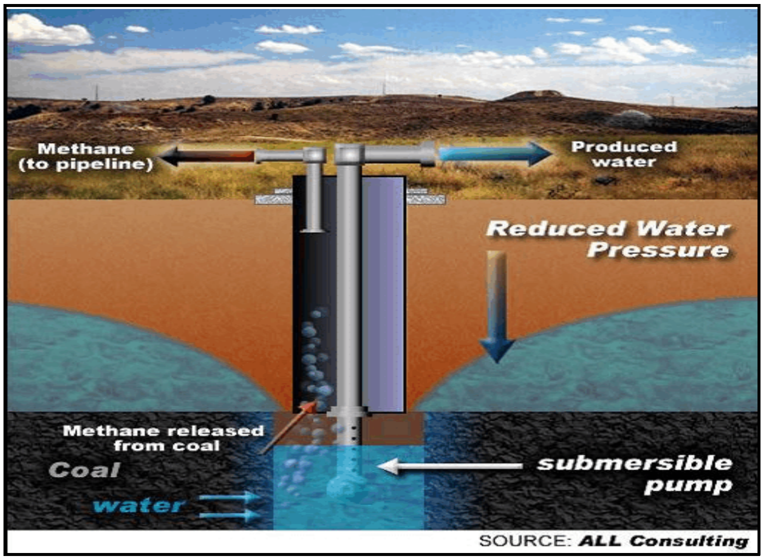

Figure 2. Methane Extraction Process.

In 2003, the Ninth Circuit Court of Appeals declared CBM product water, once brought to the surface, to be a pollutant under the 1972 Clean Water Act. This ruling has been taken to a higher court of appeals, and may be overturned yet again, but it serves to illustrate the point that this water and its potential impacts on soil, agriculture and water resources in eastern Montana and Wyoming are a principle concern among landowners, land managers, agency representatives, and environmentalists.

CBM wells in the Powder River Basin may initially discharge large volumes of water (0.4 - 1.5 liters per second), which decrease to ~ 60% of the initial rate after about two years of production. Water production continues to decrease for the life of the well (Rice et al., 2000, 2002; Robinson, 2001) (Figure 3).

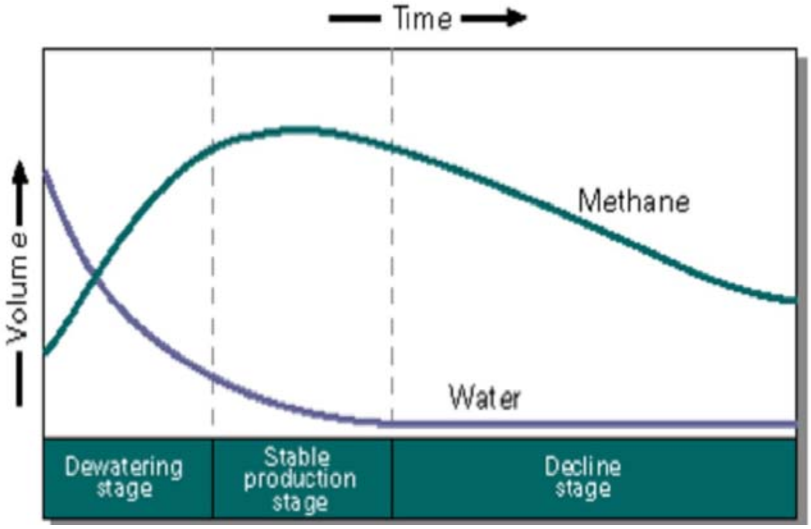

Figure 3. Typical water and gas production rates for a CBM well in the Powder River Basin. Time period is 15-20 years.

Projections for the next 10 - 15 years within the Powder River Basin call for the disposal and/or management of 308,118,700 m^3 (250,000 acre feet) of water annually from the Powder River Basin (Montana State University, 2004). At this point, economics preclude treatment of large volumes of CBM product water. Treatment becomes more economically viable if volumes are decreased and concentrations increased. Therefore, management techniques aimed at reducing CBM product water volumes may make treatment more feasible. Constructed wetlands have the potential to reduce the volume of CBM product water, resulting in less water with higher concentrations of salts and sodium through plant water consumptive use.

From the perspective of this study, there are two key issues of CBM product water management being considered. Is it possible for native, wetland plant communities to utilize substantial quantities of produced water, and is one community preferred over another for maximum water use potential?

Thesis Statement and Hypothesis

The purpose of this experiment was to assess constructed wetlands as a management option for reducing the volume of saline-sodic water co-produced in the process of CBM extraction. This was accomplished by comparing total water use and biomass production of three wetland plant communities, each consisting of three different species, irrigated with simulated CBM product water.

Native species establish hydrologically distinct communities in former ephemeral channels now running with CBM product water (Patz et al., 2002). Patz et al. (2002) identified native plant species in these channels and surrounding areas of CBM product water discharge. Negri et al. (1997) proposed that constructed wetlands could be used to reduce the amount of water co-produced by gas and oil wells. However, few assessments of the potential opportunities for wetland utilization of CBM product water have been presented in the literature.

The hypothesis was that constructed, lined, or closed basin wetland communities composed of native species would effectively reduce the volume of CBM product water that would subsequently require treatment and handling. This reduction would be accomplished through evapotranspiration of water by hydrophytic plants in the wetland ecosystem.

Objectives

The main approach of this project was to determine and compare total water use of three wetland communities managed with on-demand supply of simulated CBM product water with a low to moderate EC, high SAR chemistry. Changes in soil and water chemistry in response to CBM water additions were determined. Total water use and community biomass production for each community were recorded and used to define water use efficiency (WUE) for each community. By assessing water use, the potential role of wetland communities in managing saline-sodic water can be evaluated. This information has potential for use by land managers and developers to determine best management practices for minimizing impacts from CBM production.

LITERATURE REVIEW

Climate, Soils, and CBM Product Water in the Powder River Basin, Montana

Warm, dry summers and periods of very cold weather in winter characterize the climatic conditions of the Powder River Basin in Montana. Average daily temperature for the Powder River Basin is 7.5° C. Winter snowfall is frequent, and total snowfall is 75-100 cm, but snow cover typically disappears during milder periods. Average annual precipitation is 25-33 cm, approximately 77% of which falls between April and September, with the heaviest rains falling during late spring and early summer (USDA, 1977, 1996).

Soils in the area are often high in clays and may be salt or sodium affected themselves (USDA, 1977, 1996; Robinson, 2002; Warrence et al., 2002). A saline soil contains enough salts to adversely affect the growth of most plant species, and is defined as a soil with an EC > 4 dS/m for a saturated paste extract (Miller and Donahue, 1990; Brady and Weil, 1999; California Plant Health Association, 2002). Elevated soil salinity increases osmotic stress in plants and may result in stunted vegetative growth and reduced yields (Miller and Donahue, 1990; Hanson et al., 1999). A sodic soil is defined as having an EC < 4 dS/m and an SAR > 13 for a saturated paste extract. Excess sodium in the soil may reduce permeability of soils to water and can have toxic effects on plant growth (Miller and Donahue, 1990; Brady and Weil, 1999; California Plant Health Association, 2002). A saline-sodic soil can have adverse effects on plant growth due to high total or sodium salts, and is defined as having an EC > 4 dS/m and SAR > 13 for a saturated paste extract (Miller and Donahue, 1990; Brady and Weil 1999; California Plant Health Association, 2002).

Plants experience drought stress when they can no longer obtain water fast enough to maintain turgor pressure in cell tissues. In the soil, soluble salts can make it more difficult for plants to obtain water, resulting in drought stress even when water is not limiting. In an attempt to avoid losing water to the atmosphere and maintain turgor pressure, non-halophytic plants will close their stomates. Halophytes do not need to regulate their stomates in such situations because they have mechanisms by which they can compartmentalize, exclude, or excrete salts. This allows them to maintain plant functions such a photosynthesis as soil or water salinity increases. For example, certain species have salt glands which maintain adequate osmotic potentials by extruding salts; others have mycorrhizal fungi on roots which are thought to enhance salt tolerance (Uchytil, 1990).

Soil types typically found in areas of CBM development in the Montana portion of the Powder River Basin are alluvial smectites of marine origin which are high in montmorillonite clays. Three of the most common irrigable soils along the Powder River in Montana are from the Cherry, Marias, and Spinekop series (Fine-silty, mixed, frigid, superactive Typic Ustochrepts; Fine, smectitic, frigid Chromic Haplusterts; Fine-loamy, mixed, frigid, superactive Aridic Haplustepts, respectively)(USDA, 1977, 1996). Fine family soils, i.e. soils with the highest clay content, are at the greatest risk for dispersion by saline-sodic irrigation water (USDA, 1977, 1996; Robinson, 2002, 2003).

CBM product water quality is typically associated with elevated salinity and sodium hazards (USDI-BLM, 1999; Phelps and Bauder, 2001; Rice et al., 2002). Water quality in coal beds of the Powder River Basin is not static across the whole basin. Total dissolved solids (TDS) of waters increases in a north-west direction through the basin, and this trend is paralleled by SAR values (Rice et al., 2000; USGS, 2000; Patz, 2002; Rice et al., 2002). TDS values range from 370 ppm to 1,940 ppm (Patz, 2002), and SAR values range from 5 - 69 (Rice et al., 2002). Sodium and bicarbonate are the major constituents in CBM production waters of the Powder River Basin (Van Voast, 2003), while sulfate is almost totally absent, and concentrations of calcium and magnesium vary.

On the eastern, recharge side of the basin, calcium and magnesium concentrations are higher and sodium lower, but, as one moves toward the northwest end of the basin (farthest from recharge) the sodium concentrations almost double while calcium and magnesium are substantially lower (Rice et al., 2002; Van Voast, 2003). Chemical conditions in coal beds favor the conversion of sulfate (SO_4) to sulfide, which is then removed as a gas or precipitate. Hence, CBM production waters in the Powder River Basin contain very little SO_4 (USGS, 2000).

Once brought to the surface, CBM product water undergoes fairly rapid chemical changes. As water moves downstream, EC values increase slightly (<10%), but significant increases in SAR values (~30%) occur because the more soluble sodium remains in the water while calcium and magnesium are precipitated (USGS, 2000; Patz, 2002; Sessoms and Bauder, 2002; Van Voast, 2003). Elevated concentrations of bicarbonates reduce calcium and magnesium solubility, and a change in the partial pressure of CO_2 causes bicarbonates to undergo a reaction producing sodium, carbonate, and elevated alkalinity. Free carbonate binds with calcium and magnesium in the water to form secondary carbonate materials.

$$HCO_3^{-} + Ca^{2+} \Leftrightarrow CaCO_3(s) + H^{+} \qquad \text{[Eq. 1]}$$

Constructed Wetlands in Watershed Management

Wetlands have long been considered nature's kidneys because of their ability to filter toxins and pollutants and absorb large amounts of nutrients (Kadlec and Knight, 1995; Anonymous, 1998; Gopal, 1999). With the exception of peat bogs, natural wetlands are very productive systems that support high biodiversity and perform a variety of ecological functions (Gopal, 1999). Constructed wetlands have been gaining acceptance as replacements of natural systems which have been lost or degraded and as treatment systems to improve water quality (Cunningham et al., 1995; Peterson and Teal, 1996; Tanner, 1996; Gopal, 1999) .

Use of constructed wetlands for treatment and reclamation has increased dramatically in the past twenty years. Due, in part, to this increase in use, the Army Corps of Engineers drafted section 404 of the Clean Water Act to define, preserve and maintain natural and constructed wetlands. Wetlands are defined as areas which are inundated with water for a sufficient amount of time to develop hydric soils and vegetation (Kadlec and Knight, 1995). Section 404 provides rules and regulations governing who may construct a wetland, how discharge of water and fill from wetlands is to be handled, and how to replace or rehabilitate natural systems. Once a wetland has been created, it must be maintained in perpetuity with the exception of treatment wetlands, artificial lakes/ponds for collecting water, or other systems designed specifically for water treatment (Environmental Protection Agency, 1977).

Wastewater Treatment

Constructed wetlands are being used to treat the wastewater from dairy and agricultural operations (von Oertzen and Finlayson, 1984; Bowman, 1992; DeBusk et al., 1995). Individual households are using constructed wetlands in place of traditional septic systems, and municipalities are using them as part of their wastewater treatment operations (Boyd, 1970; Cunningham et al., 1995; Peterson and Teal, 1996; Abissy and Mandi, 1999; Shutes, 2001). Abissy and Mandi (1999) studied the purification abilities of *Typha latifolia* and *Juncus subulatus* irrigated with raw urban wastewater under arid climates. Results revealed significant reductions of organic matter in wastewater during all seasons. Nutrient removal from the wastewater was low but proved to be significantly higher in planted versus unplanted systems.

Constructed wetlands have been designed to treat storm water and urban surface runoff (Shutes, 2001), and are widely used in remediation of waters contaminated with heavy metals (Ernst, 1996; Mungur et al., 1997; Groudeva et al., 2001; Scholz and Xu, 2002). Cheng et al. (2002) assessed the ability of a twin-shaped vertical/reverse-vertical flow constructed wetland planted with the tropical species *Cyperus alternifolius* and the subtropical species *Villarsia exaltata* for removal of heavy metal contaminants in wastewater. Removal rates for the heavy metals were almost 100%, and remained stable over the five month operational period. Plant uptake was the main mechanism for removal with the majority of heavy metals accumulating in lateral roots of *C. Alternifolius* (Cheng et al., 2002). These lateral roots form a layer at the top of the oxygenated portion of the constructed wetland chamber. At the end of the treatment period, accumulated heavy metals were effectively harvested by removing the few centimeters of surface layer containing the lateral roots.

Management of Saline-Sodic Water

Although there is a large body of work reported in the scientific literature on constructed wetlands, limited research has been reported on their use in management and treatment of saline-sodic water, particularly product water from oil and gas wells.

In 1990 the Argonne National Laboratory began examining the possibility of using biological methods to optimize metal uptake and reduce the volume of water produced by oil and gas wells and which needed to be treated by mechanical means (Negri et al., 1997). The main purpose of the study was to examine effectiveness of a plant-based system in reducing the volume of water requiring treatment, effectively concentrating salts. Six species were evaluated for salinity tolerance and evapotranspiration (ET) rates in initial salinity concentrations of (15,000 and 30,000 mg/L, ~23 and 47 dS/m, respectively) with one non-saline control (0 mg/L). Mean ET rates for all six species exceeded evaporation of open water control up to a salt concentration of 20,000 mg/L (~31 dS/m), and several of the species maintained high ET rates in salt concentrations up to 60,000 mg/L (~94 dS/m). These results indicate that some halophytic and salt tolerant species have potential to maintain high water use rates and remain viable under increasingly saline conditions.

Negri et al. (1997) selected two species for further study, based on results of laboratory screening. *Spartina alterniflora* (Saltwater cordgrass) was selected for its high salt tolerance, and *Scirpus validus* (common great bulrush) for its high ET rates. A model of plant dynamics which the researchers termed a ‘bioreactor’ was developed using approximately 40% of the ET rates of the *Spartina alterniflora* and *Scirpus validus*. The bioreactor was designed to treat 66.6 m^3 (~18,300 gallons) per day of product water using a surface area of 300 m^2 (~3300 ft^2), and predicted a 75% reduction in the volume of water in less than 8 days with the resulting water having a higher concentration of salts due to reduction in volume.

Argonne National Laboratory scientists, in cooperation with Devon Energy Corporation and the Gas Research Institute, established several on-site studies at an oil and gas lease in Oklahoma. Studies were conducted using the basic model developed in the laboratory to reduce product water volume (Negri et al., 1997; Settle et al., 1998). The constructed wetland consisted of two cattle watering troughs filled with pea gravel as a growth substrate and planted with *Scirpus validus* in the first trough to maximize ET and the more salt tolerant *Spartina alterniflora* in the second trough. The system was gravity operated, required no external power, and the only maintenance cost was fertilizer to maintain optimum growth of plants. Water volume in tanks was reduced by 75% in four days, and within seven days *Spartina* leaves were coated in salt crystals. Subsequently, a second site was constructed with a third trough containing no plants to compare the evaporation rate of open water to ET rates where plants were present. Troughs with plants reduced the volume of water 30% faster than open water troughs.

Several studies at Montana State University examined effects of CBM product water on plants and soils. Preliminary results of one study indicate some agricultural and forage species, such as corn and barley remain viable and vigorous under irrigation with saline-sodic water (Levy, personal communication[1]). Another study examined effects of water quality on soil chemical and physical properties (Robinson, 2002). Four predominant soil textures being irrigated with or with the potential for irrigation along the Powder River and within the Buffalo Rapids Irrigation District were selected for the study. Two water qualities and three wetting/irrigation regimes were imposed and responses recorded. Water quality treatments consisted of either synthesized Powder River water (EC = 1.56 dS/m, SAR = 4.54, pH = 8.03) or synthesized CBM product water (EC = 3.12 dS/m, SAR = 13.09, pH = 8.22). Wetting/irrigation regimes were a one time wet/dry with each water quality, a five time wet/dry with each water quality, and a five time wet/dry with each water quality followed by leaching with 1 pore volume distilled water. Results demonstrated that electrical conductivity (EC) and sodium adsorption ratio (SAR) of soil increased as EC and SAR of applied water increased, and with increased frequency of wetting and drying. However, SAR decreased only slightly with application of distilled water while EC decreased substantially. Single wet/dry events with simulated CBM or Powder River water caused soils to have a slight increase in SAR and EC in association with the applied water. However, only about 1 in 25 of the soils sampled exceeded reported thresholds for salt injury and dispersion. With a five

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[1] Fall, 2002. Personal communication with Allison Levy, undergraduate scholar at MSU Bozeman, currently working on the effects of salinity on germination and growth of agricultural and forage crops.

time wet/dry cycle of either water quality, solution SAR and EC values increased to nearly equal the applied water, and approximately 50% of the samples exceeded thresholds (Robinson, 2003). Results of this study indicate that, in general, the major issue with CBM water application to soils is when there are repeated wetting and drying cycles. However, in a constructed wetland system soils will remain saturated so this may not become an issue.

Shortcomings of Constructed Wetlands

Constructed wetlands have several general constraints on their usefulness. Wetlands require a large amount of land per unit volume of water. A sufficient supply of water is necessary to support the wetland. Source and quality of source water may necessitate pretreatment; in some agricultural and municipal cases wastewater must be pre-treated before entering a treatment wetland (Gopal, 1999). A wetland limitation specific to cold climates is that primary functions may be minimal during winter months. Concerns for cold climate systems are low operating temperatures and ice formation on the surface. Both situations can alter hydraulic performance, lower reaction rates, harmfully impact dormant vegetation and freeze equipment (Maehlum et al., 1995).

Working with constructed wetlands in Norway, Maehlum et al. (1995), experimented with an aerobic pre-treatment stage in order to enhance nitrification and decrease biological oxygen demand (BOD), which reduces the possibility of the inlet channel becoming clogged by vegetation. Results were promising, (BOD reduction of 85-93% and N removal of 48-59%) but long-term impacts of a cold climate on performance were still unknown.

Wittgren and Maehlum (1997) provide a literature review on how cold weather conditions affect wetland processes and treatment results, and how the impacts can be handled in design and operation. The main concern with constructed wetlands in cold climates is the formation of ice. Often in winter, water in natural swamps and marshes does not freeze due to an insulating layer of snow, which is trapped by standing dead vegetation. Freezing is strongly inhibited if snow accumulates before a significant ice layer forms. Presence of some ice on the surface of a constructed wetland may be beneficial in that an ice layer acts as insulation and slows cooling of underlying water. However, if vegetation is holding ice in place, the volume of water available for flow will be reduced as the ice layer thickens. This constriction of flow may lead to flooding, the formation of more ice and possible hydraulic failure. Raising the water level in the wetland prior to freezing may create space for air and water movement without contact with the overlying ice layer. This may be a way to avoid damaging ice formation while maintaining continued functioning of the rhizosphere, albeit at decreased rates (Wittgren and Maehlum, 1997).

Another method for avoiding damaging ice formation is to divert inflow water from a wetland in late fall and atomize it into the air during winter months. Fresh water freezes (some evaporates as well), while the remaining water, now more concentrated with respect to salts, remains liquid and can be removed from the system. Researchers in the southwestern United States are experimenting with this method and are seeing promising results. Montana and Wyoming have long, cold, and fairly dry winters which may increase the practicality of using this method during winter months when wetland function and plant water use are low. One point of concern is that the process may not be as efficient with Powder River Basin product water. Product water from the southwestern U.S. has chemistries similar to sea water, while Powder River Basin product water is not nearly as saline so separation of saline and fresh water may be an issue in the Powder River Basin.

The Role of Plants in Phytoremediation

Phytoremediation, or bioremediation, is the concept of using plant-based systems and microbiological processes to counteract or eliminate contaminants in nature. These remediation techniques, which utilize specific planting arrangements, constructed wetlands, reed beds, floating-plant systems and numerous other configurations, have been common in the treatment of many types of wastewater, and lately, contaminated soils and atmospheric pollutants (Cunningham et al., 1995; Anonymous, 1998).

Advantages of phytoremediation are that systems are generally low-cost and low-tech with little maintenance expense, although there are some limitations. Remediation is best considered a long-term process since it is usually slower than chemical treatments; levels of parameters targeted must be within the tolerance limit of selected plants; and containment may be needed in the case of highly soluble contaminants which may leach out of the root zone (Cunningham et al., 1995).

Wetland Plants, Halophytes, Community Dynamics

Plants utilize one of three basic phytoremediation strategies; 1) phytoextraction/bioaccumulation: plants accumulate contaminants and are harvested in order to remove contaminants from the system; 2) phytodegradation: contaminants are converted into non-toxic materials by plants and associated microorganisms; 3) phytostabilization: contaminants are precipitated out of solution or absorbed/entrapped in the soil matrix or plant tissue (Cunningham et al., 1995).

An example of a phytoextractor is *Spartina alterniflora*: salts are accumulated in plant leaves, and when harvested, accumulated salts are effectively removed from the system. There is an added cost-reduction benefit in that *Spartina alterniflora* can be used as forage for cattle. Plants are readily consumed and salt-covered leaves have not been seen to be harmful to cattle (Settle et al., 1998).

Rangeland of Wyoming/Montana contains many native and culturally significant species that could potentially be threatened by non-native species. *Spartina pectinata* (Prairie cordgrass) is native to the area and may be a viable alternative in areas where *S. alterniflora* could be considered a potential weed. Cattails and rushes, while not all natives, may be useful because of salinity tolerance, high water use, and when the water source is removed, plants should absquatulate with the water and not become a problem.

Qadir et al. (2001) evaluated phytoremediation techniques on a calcareous saline-sodic soil (EC=24-32 dS/m, SAR=57-78 in top 0.15 m depth) planted with wheat (*Triticum aestivum L.*) in winter and rice (*Oryza sativa L.*) in summer, and irrigated with sodic and moderately saline water (EC=2.9-3.4 dS/m, SAR=12-19.4). Soils in this study were classified as Calcic Haplosalids. Original soil EC values were 24-32 dS/m at the surface to 0.15 m depth, and decreased to ~ 7 dS/m at the lowest sampling depth (0.9 - 1.2 m). After one crop each of wheat and rice, the final surface EC values were about 10

+/-1 dS/m in all treatments. The SAR for the profile to 1.2 m depth was reduced from ~31 to ~15 in all treatments, indicating that a significant amount of the excess sodium in the soil was leached below the 1.2 m depth.

Plant Water Consumptive Use and Evapotranspiration (ET)

Idso (1981) reviewed a number of experiments addressing plant water use and evaporation to determine whether vegetation helped or hindered evaporation. Over the years, some researchers have found evaporation from open water to exceed ET of vegetated surfaces (Idso, 1981; Snyder and Boyd, 1987; Lafleur, 1990, Allen et al., 1992; Glenn et al., 1995; Negri et al., 1997; Pauliukonis and Schneider, 2001), while others have concluded there is no difference (Idso, 1981; Lafleur, 1990). Some of this disagreement may be due to differences in experimental design, i.e. small, exposed lysimeters. There are also inherent differences in ET rates among plant species and communities and there is no standardized method for determining ET rates. Based on theoretical and experimental evidence, Idso concluded that evaporation from an extensive, open body of water would not significantly increase with the introduction of vegetation. In reality, the vegetation may in fact lower the evaporation rate. However, introduction of vegetation on a body of water of more limited extent may increase evaporation if vegetation remains robust.

Pauliukonis and Schneider (2001) conducted a study along the southern shoreline of Oneida Lake, NY, USA. Results showed that *Typha latifolia L.*(broad-leaved cattail) had higher ET rates per unit leaf area (mm/mm^2 per day) than open water or bare soil and used an average of 5.75 +/- 1.34 mm of water per day. Researchers used the lysimeter method to determine daily ET rates in order to obtain consistent water use data across different substrates, plant forms and without interference of meteorological conditions. As the summer progressed, ET increased. Researchers suggest this was due to the ability of *T. latifolia L.* to increase the number of ramets from 5-8 at the beginning of summer to 8-20 at the end of the summer. Researchers also noted that *T. latifolia L.* did not show the typical midday drop in ET rates. They attributed this to claims by Leverenz (1981), Schulze et al. (1985), and Bernhoffer and Gay (1989) that plants with a constant supply of water do not need to regulate their stomata in order to conserve water in their leaves.

Studies by Snyder and Boyd (1987), Glenn et al. (1995), and Negri et al. (1997) agree with the results obtained by Pauliukonis and Schneider that show ET from vegetated areas to exceed evaporation from open water.

Water Use Efficiency

Most of the water use efficiency (WUE) research being conducted is concerned with improving WUE due to concerns about limited water resources in both irrigated and non-irrigated agriculture (Hatfield et al., 2001; Howell, 2001; Pikul et al., 2004). Water use efficiency is used to interpret how efficiently plants use water to produce biomass, and is a relative value used to assess and compare consumptive water use among species. WUE is defined as biomass or harvestable crop or commodity per unit of water use, typically expressed as grams of grain or dry matter divided by kilograms of water, and is calculated by dividing the total above-ground or harvestable biomass produced by the total water used (Hatfield et al., 2001; Larcher, 2001; Pikul et al., 2004).

The shortcomings of using WUE is that it is a ratio which is highly dependent on biomass. Biomass production is a function of plant physiology while water use is a function of plant maturity, stress, water availability, and environment.

A water use efficiency ratio brings data from physically and physiologically different plant species to a common scale for analysis. The problem with comparing WUE's of different crops or plants species is that there are no standard metrics for computation.

It has been postulated that WUE is a nebulous term because plants loose water to the atmosphere rather than use it as raw material for biomass production. Researchers have used terms such as 'transpiration efficiency' or 'precipitation efficiency' interchangeably with WUE although they are not technically correct (Hatfield et al., 2001). WUE is based on evaporation and transpiration, and the term transpiration efficiency suggests evaporation is not considered. Precipitation efficiency is a measure of the dry matter produced per increment of precipitation. This is different from WUE in that WUE takes into account water from irrigation as well as precipitation.

Transpiration ratios are another method for assessing the efficiency of plant water use in biomass production. A transpiration ratio is the mass of water needed for a plant to produce a unit mass of dry plant material and is the inverse of WUE.

WUE depends on site-specific climatic conditions, and values for the same species will differ substantially over locations. WUE is impacted by evaporative demand which is driven by vapor pressure gradients between leaf and air. Evaporation can be influenced by temperatures, humidity and precipitation and/or irrigation events.

There are many ways of expressing plant consumptive water use, and one must be aware of how water use and crop production are expressed in order to properly evaluate responses. For this paper WUE is defined as grams of oven dry above ground biomass produced over the growing season divided by kilograms of water used over the growing season, because it is the best known and most widely used term today.

$$WUE = \frac{Total\,biomass\,(g)}{Total\ water\ used\ (LorKg)} \qquad [\text{Eq. } 2]$$

Thinking Outside the Well

Problems associated with management of saline-sodic soil and water are not solely related to the CBM industry. Irrigated regions of the world, particularly arid and semi-arid areas, have been contending with salinity issues since the beginning of recorded history (Hanson et al., 1999). Many portions of the world are struggling with saline-sodic soil and water issues and research into beneficial use and management of saline-sodic water could have global implications. In 1995 it was estimated that 25% of the worlds' irrigated land was damaged by salinity, and not a single continent was free of this impact (Batlle-Sales, 1995).

Anthropogenic or secondary salinization is as old as irrigation, but has been rapidly expanding since the 1950's. Development of large scale irrigation systems and clearing of land with replacement of trees and native deep-rooted vegetation with shallow rooted crops have been the major causes of secondary salinization since the end of WWII (Batlle-Sales, 1995; Ghassemi et al., 1995; Qadir et al., 2001; Barrett-Lennard, 2002; Turner and Ward, 2002).

Agricultural water requirements already far exceed supplies in nearly 80 countries

(Qadir et al., 2001). The worlds increasing need for irrigable acreage is putting marginal land into agricultural use and using marginal waters for irrigation, resulting in adverse affects to soil and water resources. Many parts of the world experience natural or primary salinity due to geology, soil type, climate, and hydrology. Naturally occurring discharge of saline groundwater to surface water sources, compounded by agricultural and mining wastewater discharged into river systems, has led to a global increase in soil and water salinity and sodicity (Batlle-Sales, 1995; Ghassemi et al., 1995; Jayawardane et al., 2001). In Australia, primary salinity is extensive but agricultural development has led to extreme stream salinization (Barrett-Lennard, 2002; Turner and Ward, 2002). Thirty-six percent of the divertable surface water of Australia is no longer potable and sixteen percent is of marginal quality (Ghassemi et al., 1995). Clearing of native vegetation for annual crops and pastures in Australia is a major cause of water logging and secondary salinity in many catchments, particularly southwestern Australia (Turner and Ward, 2002). Studies suggest that agricultural systems in Australia allow 20-100 mm of rainfall to infiltrate past the root zone, compared to estimates of 5 mm or less of deep drainage under pristine, native vegetation. Deep drainage to groundwater results in a rising water table, which causes water logging and secondary salinity.

Lack of adequate drainage and high water tables in Argentina are increasing salt concentrations in soils (Ghassemi et al., 1995). Irrigation with low quality water and inadequate drainage coupled with low rainfall and high evaporation rates are causal factors of salinity in Iran (Ghassemi et al., 1995). Nationally, South Africa has the problem under control, but over-irrigation on soils with poor drainage and discharge of industrial effluents exacerbated by excessive primary salinity is still a concern in some areas (Ghassemi et al., 1995). Egypt has fairly well-drained soils, but natural drainage cannot keep pace with increasing irrigation, so water tables are rising and salts accumulating (Helalia et al., 1992; Ghassemi et al., 1995). India and Pakistan are experiencing salinity problems associated with poor irrigation practices, and in northeast Thailand deforestation has led to increased salinity (Ghassemi et al., 1995). The heavy clay soils of coastal Thailand and China are naturally saline from seawater, and in the Commonwealth of Independent States (former USSR) natural factors are the main cause of salinity (Ghassemi et al., 1995). Irrigation and dryland farming, coupled with low rainfall and high evaporation rates in arid and semi-arid regions, are leading causes of secondary salinity in the western U.S. (Batlle-Sales, 1995; Ghassemi et al., 1995).

MATERIALS AND METHODS

System Design and Water Chemistry

Twelve closed-system wetland cells (i.e. lysimeters) were constructed using galvanized steel stock tanks, approximately 3 m long, 1 m wide, and 0.6 m deep, painted inside with marine grade paint/epoxy to prevent corrosion from the simulated product water. Pits were excavated and lysimeters placed with the top edge of each lysimeter approximately 5 cm above ground level to reduce non-uniform heating, cooling and ET due to positional effects from sun and wind (Figure 4).

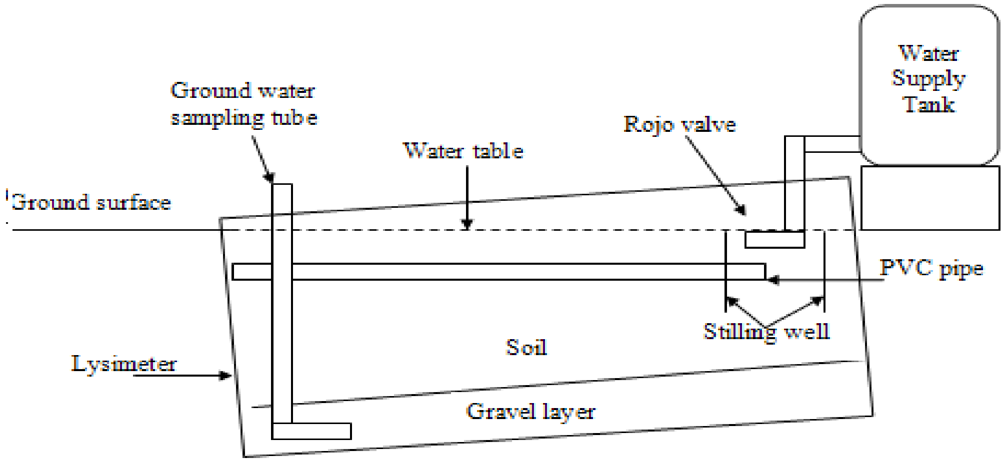

Figure 4. Schematic of lysimeter construction and installation.

Each lysimeter was set on a 2% grade to aid gravitational water flow. Lysimeters were filled to a depth of 15 cm with washed gravel (2 - 2.5 cm diameter) to maintain proper water movement and equipped with a sampling tube at the lowest point for water sampling. Weed barrier cloth was installed over the gravel and covered with 46 cm of soil. Perforated PVC pipe was installed on an even grade in conjunction with the desired water table height at the low end of each lysimeter (Figure 4). This facilitated horizontal water movement in each lysimeter. A stilling well was installed at the upper end of each lysimeter and PVC pipe set at the bottom of each well. Jobe Rojo™ float valves were attached to water delivery tanks and set in stilling wells (Figures 5 and 6). As evaporation and transpiration by plants caused a drop in the water table, float valves released water from supply tanks, thereby maintaining water table height at the soil surface of the low end of each lysimeter.


Figure 5. Rojo® valve in stilling well.


Figure 6. Installed and planted lysimeters.

Soil selection criteria for filling the lysimeters were based on information about soils in the Powder River Basin most likely to be adversely affected by CBM product water discharge. Well-drained, fine family soils with smectitic soil mineralogy and limited soil organic matter that occurred within a reasonable transport distance from Montana State University were targeted. Based on Gallatin County Soil Survey and local knowledge, Dr. Tom Keck, formerly with the NRCS, identified soil map units having a high probability of meeting the search criteria. Soil survey maps showing the locations of potentially suitable map units were created using Arc-View software by Katie Alvin, with the Bozeman NRCS field office (Tom Keck, Katie Alvin, USDA-NRCS, personal communications[2]). The search area was further refined to include proximity to primary roads and landowner willingness to participate in the project. After reviewing soil maps, a site south of Three Forks, Montana was identified as a prime candidate for obtaining suitable soil material. This site had been mapped as the Patouza-Abor Complex, 2 to 8 percent slopes with parent material dominated by montmorillonite clays (USDA, 2002). The Patouza soil series is a fine, smectitic, frigid Torrertic Argiustoll, and the Abor series is classified as a fine, smectitic, frigid Aridic Leptic Haplustert (USDA, 2002). Field verification sampling was completed by Dr. Tom Keck and myself. Six soil pits were sampled to examine soil properties and check classifications. Soils at the site did not match those described in the soil survey as heavy textured upper horizons in the soils sampled were underlain by sandy substrates at variable depths. Field classification of

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[2] Spring 1999. Personal communication with Katie Alvin of the Bozeman NRCS office. Personal communication and field work with Tom Keck, formerly of the NRCS.

soils sampled was clayey over sandy, smectitic over mixed, frigid Torrertic Haplustolls.

Particle size analysis of field samples was completed to evaluate clay content and soil texture, and followed protocol outlined in Gee and Bauder, 1986 (Appendix A). Overburden soil (0-15 cm) was removed from the source location to minimize weed seed contamination and remove depositional material from upland erosion. On the basis of determination of texture and clay content (Appendix A), soil from a depth of 16 - 60 cm was bulked for use in the project, and samples analyzed for baseline soil chemistry. This soil material was used to fill each lysimeter.

To prevent introduction of potential weed species, native plant species found in areas of CBM product water discharge were selected for this study. Nine species among those catalogued by Patz et al. (2002) were selected and grouped into three communities. Table 1 lists the species in each community and the abbreviations which will be used throughout the rest of this paper.

Table 1. Plant communities and abbreviations.

Community 1 Maritime/saltgrass/spikerush
Maritime bulrush (*Scirpus maritimus)*
Inland saltgrass (*Distichlis spicata*)
Creeping spikerush (*Eleocharis palustris*)

Community 2 Cattail/cordgrass/wildrye
Common cattail (*Typha latifolia*)
Prairie cordgrass (*Spartina pectinata*)
Canada wildrye (*Elymus canadensis*)

Community 3 American/baltic/WG
American bulrush (*Scirpus americanus*)
Baltic rush (*Juncus balticus*)
Streambank wheatgrass (*Pascopyrum smithii*)

Plant selection was based on: water use; salinity tolerance; mode of reproduction (rhizomes vs. seeds); forage quality; presence of dense, fibrous root systems to support an active rhizosphere and act as biolfilters; or some combination of these traits (Appendix B). Appendix C provides detailed descriptions of the nine species selected for this study.

Lysimeters were divided into three equal regions (lower, middle and upper), and each plant species was assigned to one region (Figure 7). Plants were assigned a region based on field observations completed by Patz et al., 2002. Once lysimeters were installed and filled with soil, each of the three plant communities was randomly assigned to four of the twelve lysimeters (Table 2).

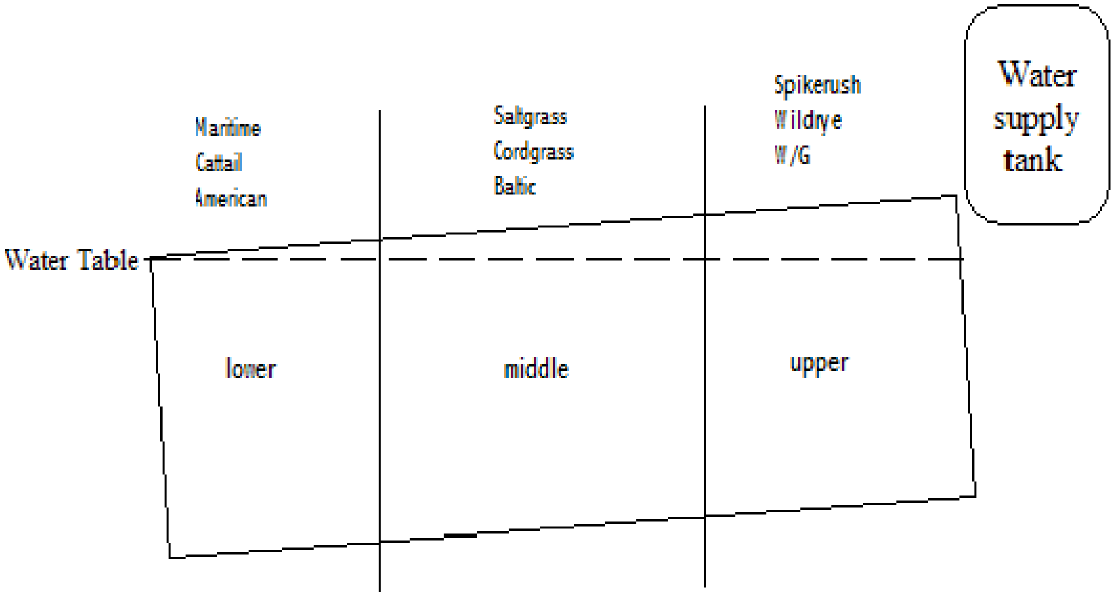

Figure 7. Designation of lysimeter positions for plant species and soil sampling.

Table 2. Assignment of communities to lysimeters.

Lysimeter Number	1	2	3	4	5	6	7	8	9	10	11	12
Community Number	3	2	1	1	3	2	1	2	3	1	3	2

Multiple runs of MINTEQA2 (Allison et al., 1991), a geochemical program for modeling groundwater chemistry, identified appropriate reagent combinations needed to synthesize treatment water qualities. Target treatment water chemistry simulated CBM product water of the Montana portion of the Powder River Basin and all twelve lysimeters received the same simulated water, it being EC ~ 3 dS/m and SAR ~ 25 (Appendix D).

A greenhouse canopy was constructed over the study site to modify ambient air and soil temperatures and growing season length and to maintain precipitation inputs comparable to conditions within the Powder River Basin. The canopy also served to eliminate uncontrolled precipitation events (Figure 8).

Figure 8. Canopy over plots.

Operation and Sampling

This experiment was designed around a basic water balance equation which allows for the determination of ET as follows:

$$ET = P + I - DR - RO - \Delta W \qquad \text{[Eq. 3]}$$

where ET = evapotranspiration, P = precipitation, I = irrigation, DR = drainage and deep percolation, RO = runoff and ªW = soil water depletion (Or et al., 2002). In the present study, precipitation was excluded from the calculation of ET by the greenhouse canopy. Since each lysimeter was a closed system, deep drainage (DR) and runoff (RO) were non-existent, and all lysimeters were supplied water on the basis of evaporative demand, thereby negating soil water depletion (i.e. ªW). The result was a simplified water balance equation,

$$ET = I \qquad \text{[Eq. 4]}$$

where irrigation (water supply rate) was controlled and monitored. The water supply rate (I) was regulated by ET rates.

By assessing evapotranspiration, the potential role of these communities in managing volumes of water associated with CBM extraction in the Powder River Basin was characterized and quantified.

A single Class A evaporation pan was installed under the canopy and supplied with the same water as the lysimeters received (EC ~ 3.4 dS/m, SAR > 25). Pan evaporation was determined manually on a weekly schedule. Water use was determined on a weekly schedule for each lysimeter with water supplied via calibrated supply tanks. Supply tanks were maintained and covered to minimize evaporative losses, and manual measurements of the amount of water depleted from supply tanks were made each week. At harvest, these water use amounts were converted to equivalent depths. This was done by first multiplying liters of water used by 1000 to get cm^3 of water used during the growing season.

$$WaterUse(cm^3) = WaterUse(L) * 1000 \qquad \text{[Eq. 5]}$$

Total water used (cm^3) was then divided by the surface area of each lysimeter (cm^2) resulting in equivalent depths of water used in centimeters.

$$EquivalentDepth(cm) = \frac{WaterUse(cm^3)}{SurfaceArea(cm^2)} \qquad \text{[Eq. 6]}$$

Ground water samples were collected from the gravel substrate at the lowest end of each lysimeter monthly and analyzed to characterize changes in water chemistry. Soil samples from each region (lower, middle, upper) of every lysimeter were collected at the end of the season to determine changes in soil chemistry. Community biomass production and cumulative water use (L) were determined at the end of the season and used to determine water use efficiency (WUE) for each community.

Laboratory Analysis

All chemical analyses of samples reported herein were conducted by AGVISE Laboratories of Northwood, ND and MDS Farmer Services (Harris Laboratories) in

Lincoln, NE. All water samples were sent to AGVISE for analysis of calcium, magnesium, sodium, EC and pH, and results reported in parts per million (ppm). All soil samples were oven dried (105EC), sieved (2mm) and sent to Harris Laboratories for analysis of soluble saturated paste extracts and exchangeable base cations. Results of soil analysis were reported as mg/L, meq/100g, and % CEC. In an effort to achieve consistency in test procedures and sample analysis, these same laboratories completed all soil and water quality analyses for this study.

Statistical Analysis

All statistical analyses were conducted using R version 1.7.1 statistical software (R Development Core Team, 2003). Single factor ANOVA's with community as a factor were conducted on total water use, biomass and WUE, with the main focus based on total water use. Significant differences at P#0.05 were determined using a multiple comparison procedure for equal sample sizes.

There are four basic assumptions for fixed factor level ANOVA models which were applied to these data; 1) for each factor level, the response variable is normally distributed; 2) homogeneity of variance; 3) for each factor level, the responses are random samples from the distribution associated with that level; 4) responses for each factor level are independent of the responses for any other level (Neter et al.,1996).

RESULTS

Statistical Analysis

ANOVA models are fairly robust against minor departures from model assumptions (Neter et al., 1996), but residual plots can be helpful in identifying serious departures and determining if the ANOVA model being used is appropriate. Diagnostic plots are shown for WUE only as total water use and biomass production showed similar results with respect to model assumptions.

Figure 9 is a plot of the fitted values (or predictor variables) against the residuals for WUE of each lysimeter, with WUE in grams of biomass per kg water used on each axis. This plot is one of the most important plots in determining any major departures from ANOVA model assumptions. From this plot lack of substantial departures from homogeneity in the variance can be confirmed, outliers detected, and the appropriateness of the ANOVA model determined. Each community is along the X-axis and the four replications are represented by four vertically stacked dots. Notice how most dots appear to fall within a horizontal band about 0 and the lack of any identifiable patterns in the way residuals depart from 0. This indicates the one-way ANOVA model was appropriate.

Homogeneity of variance can also be determined from this plot. Residual values that form patterns resembling a funnel, a frown or have positive/negative slope indicate variances are not homogenous and transformations may be necessary. Data in Figure 9 form no such patterns, indicating error variances are homogeneous. One interesting thing to note about this plot is the locations of the community replications. Two communities are grouped just below 0.7 on the X axis while the third is above 1.1. This indicates that, although there are no serious deviations from homogeneity in the variance, mean WUE is different with respect to community.

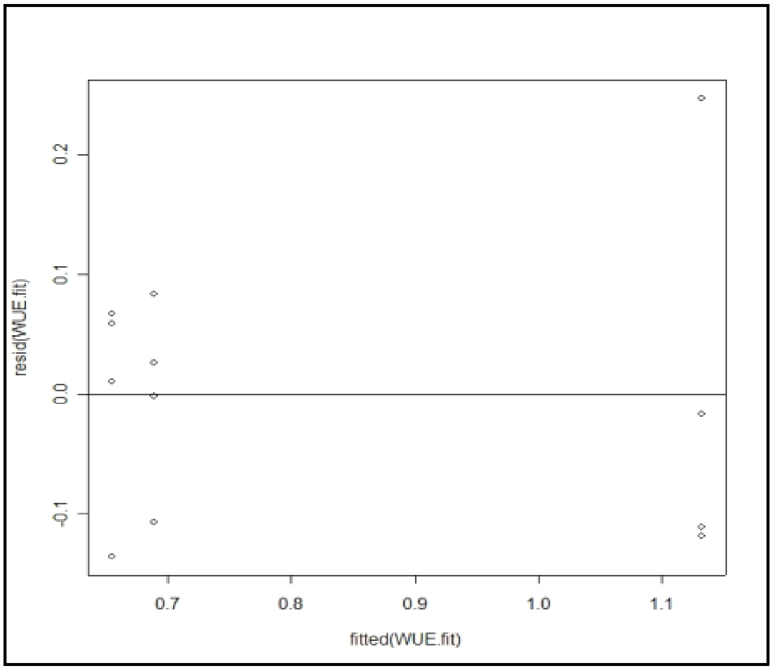

Figure 9. Plot of fitted vs. residual WUE's for each lysimeter. WUE is in g/kg on both axis.

A fitted vs. residual plot is also helpful in identifying outliers, as they will affect distribution of plotted values, but they are more easily identified by a box plot. Figure 10 is a boxplot showing median, 1st and 3rd quartiles and maximum/minimum WUE for each community. WUE in grams of biomass per kg water used is on the Y axis with each community along the X axis. Median WUE is represented by the line through each box while minimum and maximum WUE values are shown by the lines extending above and below each box. Boxplots show summary information about the symmetry of the residuals and possible outliers, and are used to determine departures from the assumptions of normality and equal variance. Figure 10 confirms there are no outliers in the data set as outliers are identified by open circles above or below boxes. Communities 1 and 2 appear to be slightly skewed, most values are below the median for community 1 and above the median for community 2, but overall there are no serious departures from normality.

There also appear to be no major departures from the assumption of equal variance because the data have similar spreads, that is, the boxes and tails have similar ranges in values. Notice how all three boxes are in different locations along the Y axis. This confirms what was seen in Figure 9, that although there are no serious departures from the assumption of homogeneity of variance, there is a difference in mean WUE with respect to community.

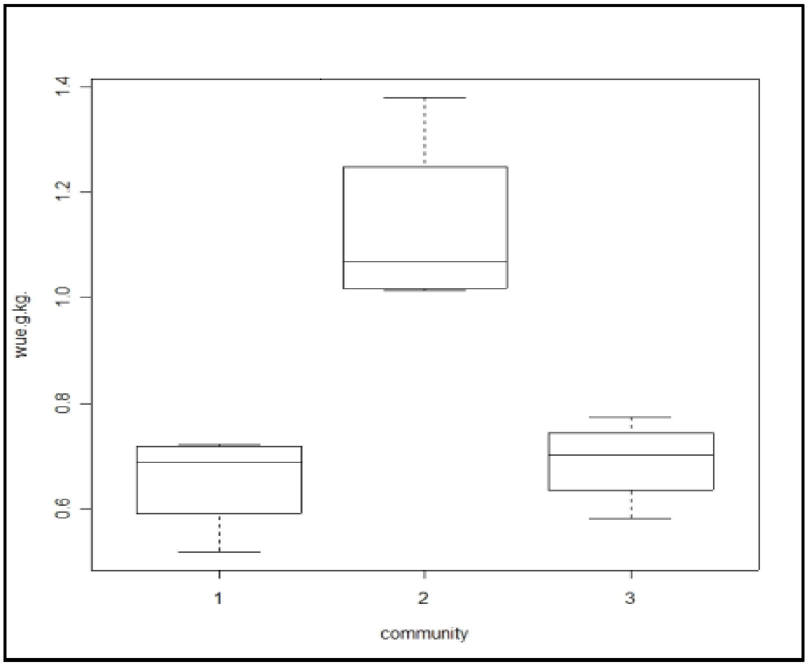

Figure 10. Boxplot showing median WUE, 1st and 3rd quartiles and variance for each community along the X axis. WUE is in g/kg on the Y axis.

Figure 11 is a normal probability plot of residuals against expected values under normality. If residuals are distributed normally, a linear pattern is seen about the regression line. The pattern seen in Figure 11 indicates the error terms are normally distributed.

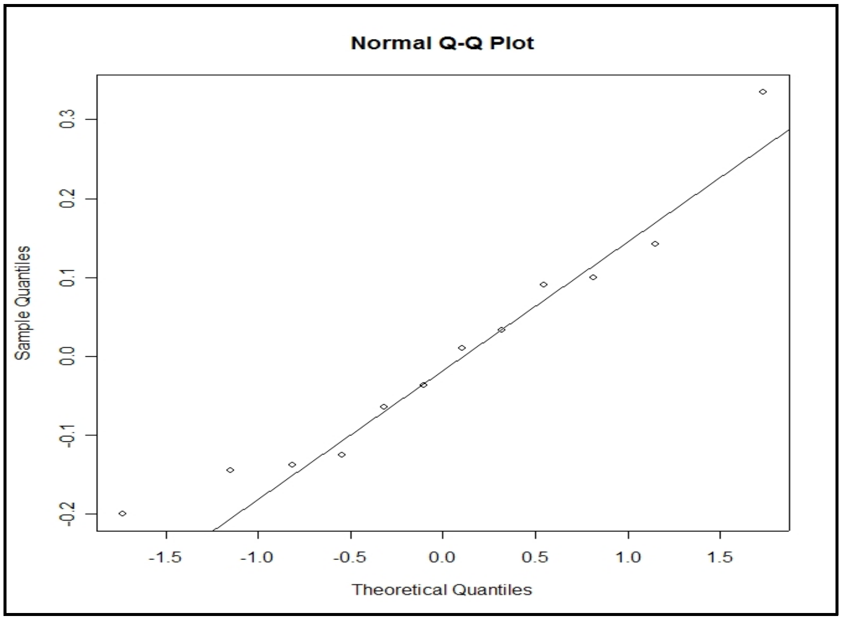

Figure 11. Normal probability plot showing data points along a theoretical regression line. WUE is in g/kg on both axis.

Plant Performance and Water Use

ANOVA results indicated there was no statistically significant difference in mean water use over the growing season with respect to community (P = 0.05), even though differences were observed (Table 3, Figure 12). Maritime/saltgrass/spikerush and Cattail/cordgrass/wildrye communities had rates within 16 liters of each other (1100 and 1116 L, respectively), while the American/baltic/WG community used 950 liters. Graphically, this may seem like a large difference, but statistically it is not significant.

Table 3. ANOVA tables for total water use, total biomass, and WUE.

```
Analysis of Variance Table

Response: H2O
              Df     Sum Sq       Mean Sq     F value     Pr(>F)
community     2      23797        11899       1.7417      0.2294
Residuals     9      61484         6832
---
Response: BIOMASS
              Df     Sum Sq       Mean Sq     F value     Pr(>F)
community     2      846163       423081      21.779      0.0003558 ***
Residuals     9      174833       19426
---
Response: WUE (g/kg)
              Df     Sum Sq       Mean Sq     F value     Pr(>F)
community     2      0.56749       0.28375    19.155      0.0005713 ***
Residuals     9      0.13332      0.01481

*** Significant at % = 0.05
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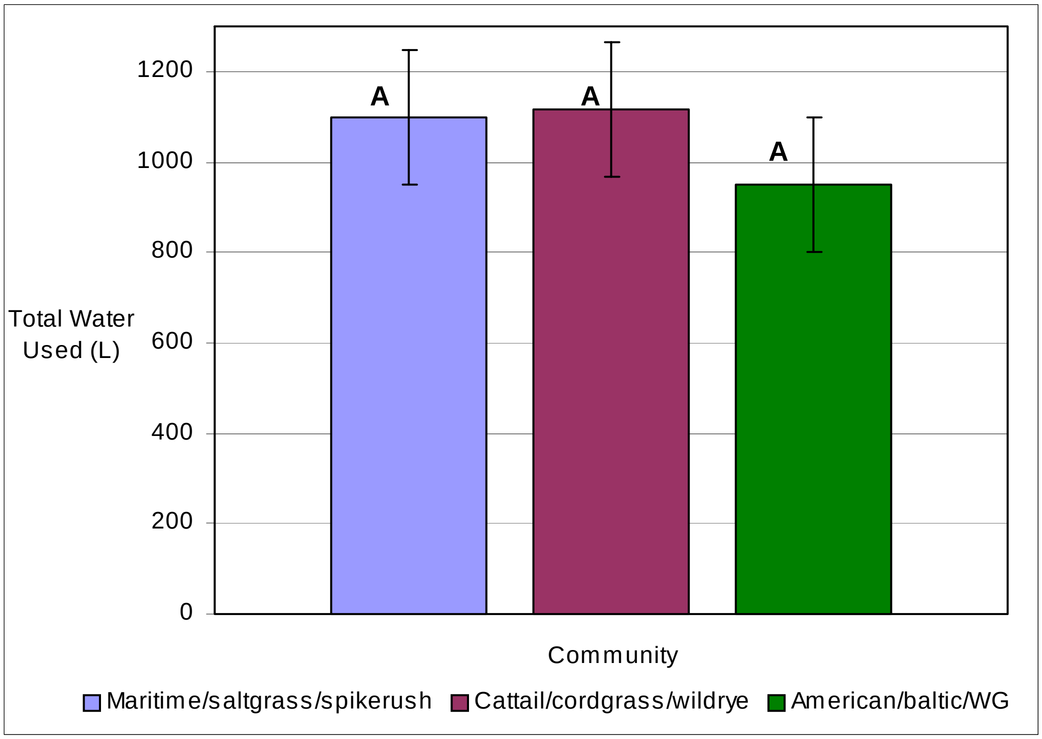

Figure 12. Average total water use for each community in 2004. Letters indicate statistically similar values for water use. Error bars represent +/- one standard deviation.

ANOVA confirmed that mean biomass and WUE's differed significantly with respect to community (P = 0.05) (Table 3). Biomass production for the Cattail/cordgrass/wildrye community was significantly higher than the American/baltic/WG or Maritime/saltgrass/spikerush communities, which had statistically similar biomass production (Figure 13).

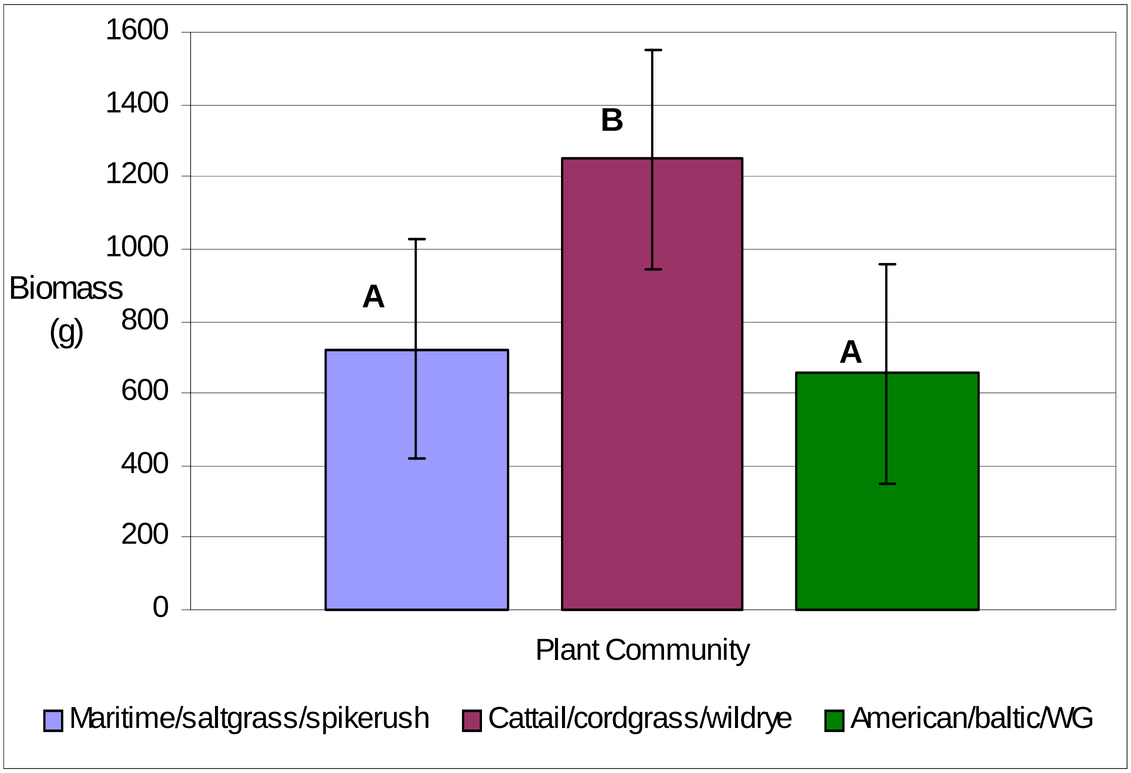

Figure 13. Average community biomass production for 2004. Letters indicate statistically similar biomass values. Errors bars represent +/- one standard deviation.

Recall that WUE is dependent on biomass, so significant differences in biomass production will be reflected in WUE. Recall also that WUE is a ratio of biomass produced per unit water used, and a lesser ratio indicates less efficient use of water compared to a greater ratio. WUE's for the Maritime/saltgrass/spikerush and American/baltic/WG communities are less than the WUE of the Cattail/cordgrass/wildrye (Figure 14). That is, less biomass was produced per unit of water used in the Maritime/saltgrass/spikerush and American/baltic/WG communities.

Results of mean separations indicate mean WUE for the Cattail/cordgrass/wildrye community was significantly different from mean WUE's of the Maritime/saltgrass/spikerush or the American/baltic/WG communities, and that the Maritime/saltgrass/spikerush community was statistically similar to the American/baltic/WG community, as is illustrated by identical letters in Figure 14.

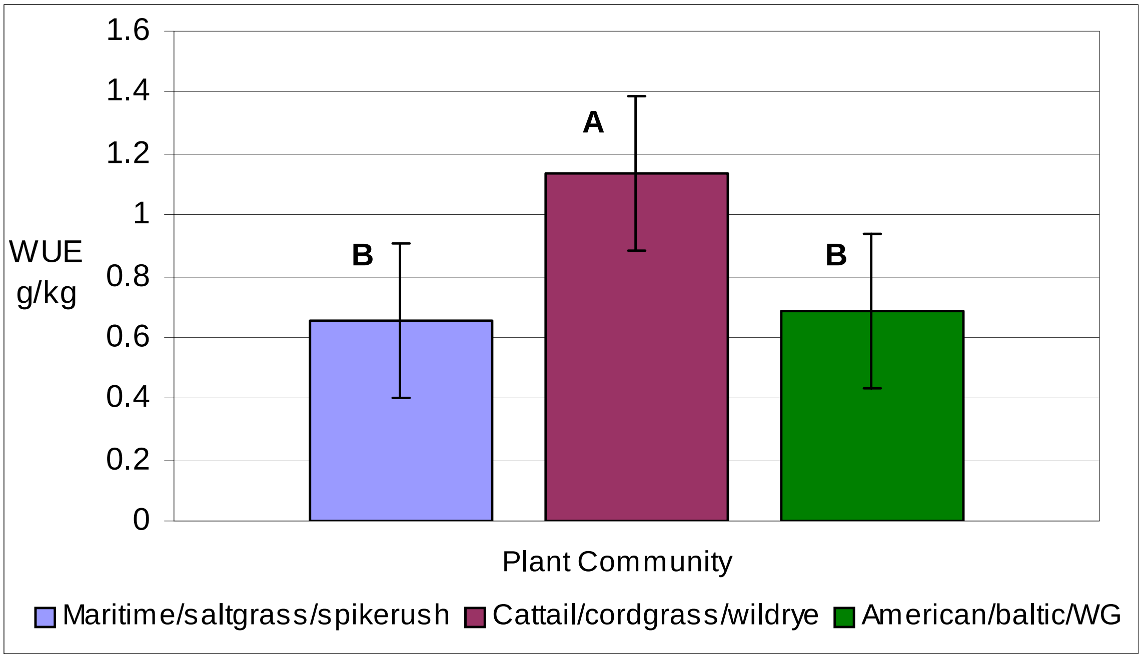

Figure 14. Average community WUE for 2004. Letters indicate statistically similar values for average WUE. Error bars represent +/- one standard deviation.

Class A pan evaporation exceeded that of each community during the growing season (Figure 15). This situation may have resulted from the pans' location. It was placed on the open, southern edge of the canopy. Shade cloth was installed, but evaporation may have been impacted by edge effect due to fluctuations in solar radiation, ambient temperature and wind.

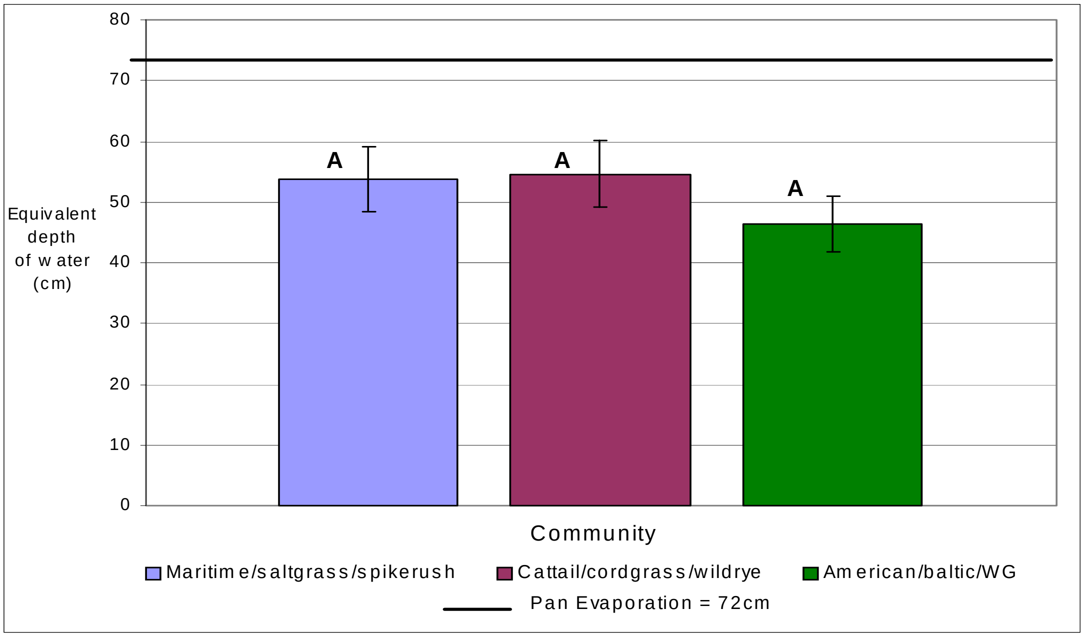

Figure 15. Average equivalent depth of water used (cm) by each community and Class A pan evaporation for 2004. Letters indicate statistically similar values for average equivalent depth of water. Error bars represent +/- one standard deviation.

Soil and Water Chemistry

Figures 16, 17, 18 and 19 illustrate how plant water consumption affected ground water chemistry (EC, SAR, pH) from beginning to end of this study. Notice how similar groundwater EC dS/m is at the beginning of the growing season (Figure 16, Sample Date 1), and how much variability is seen by the end of the study (Figure 16, Sample Date 6).

Figure 17 shows the average EC dS/m of the four replications for each community. By the end of the study, evapoconcentration due to evaporation and plant consumptive use resulted in an increase in average EC for all communities.

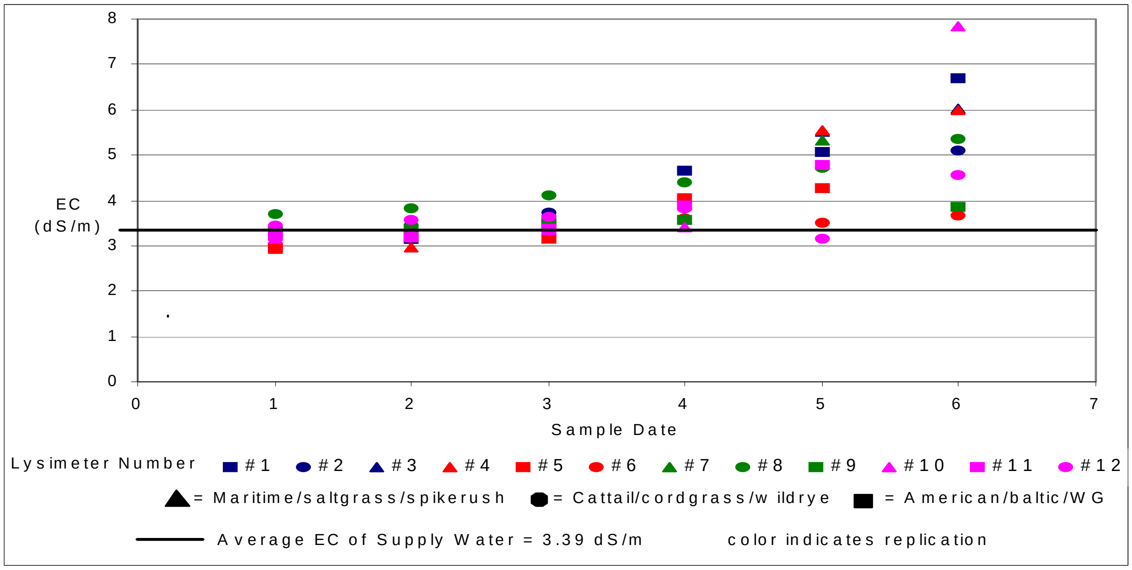

Figure 16. Groundwater EC (dS/m) for each lysimeter from March - September 2004. Average EC of supply water (3.39 dS/m) represented by the solid line.

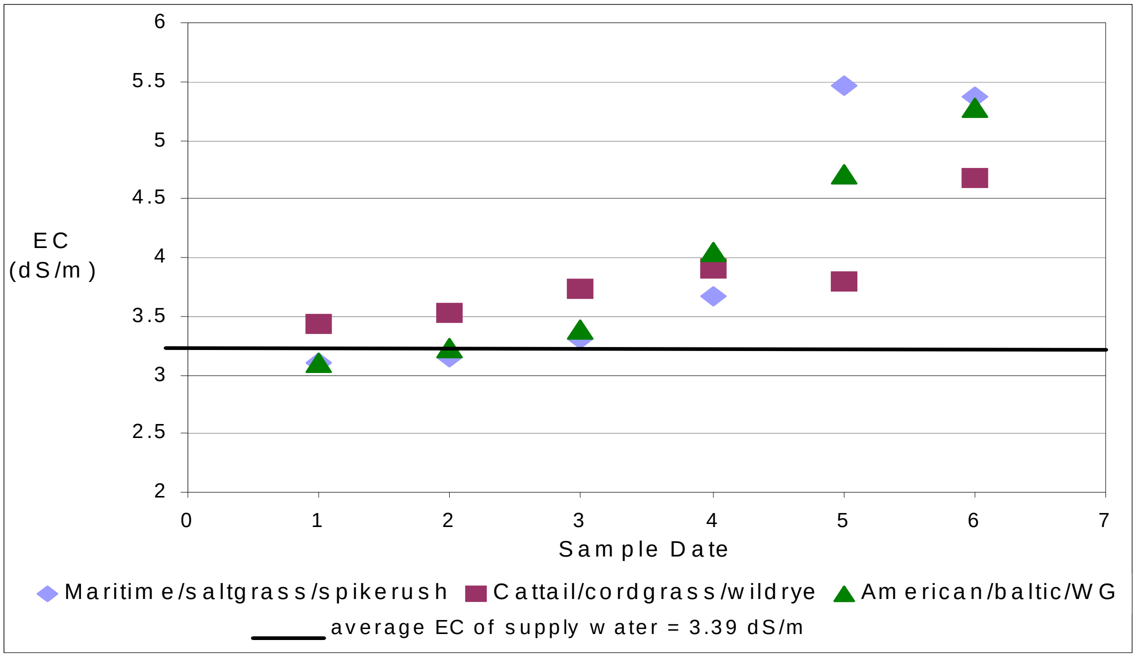

Figure 17. Average groundwater EC for each community (dS/m) from March - September 2004. Average EC of supply water (3.39 dS/m) represented by the solid line.

Figures 18 and 19 show average groundwater SAR and pH for each community from the first sampling date in March to the last sampling date in September of 2004. There was a general decrease in SAR (Figure 18) and pH (Figure 19) during the first four months of the season, and an increase in both at the end of the season. The average SAR of the supply water was 26.3 and average pH was 8.22.

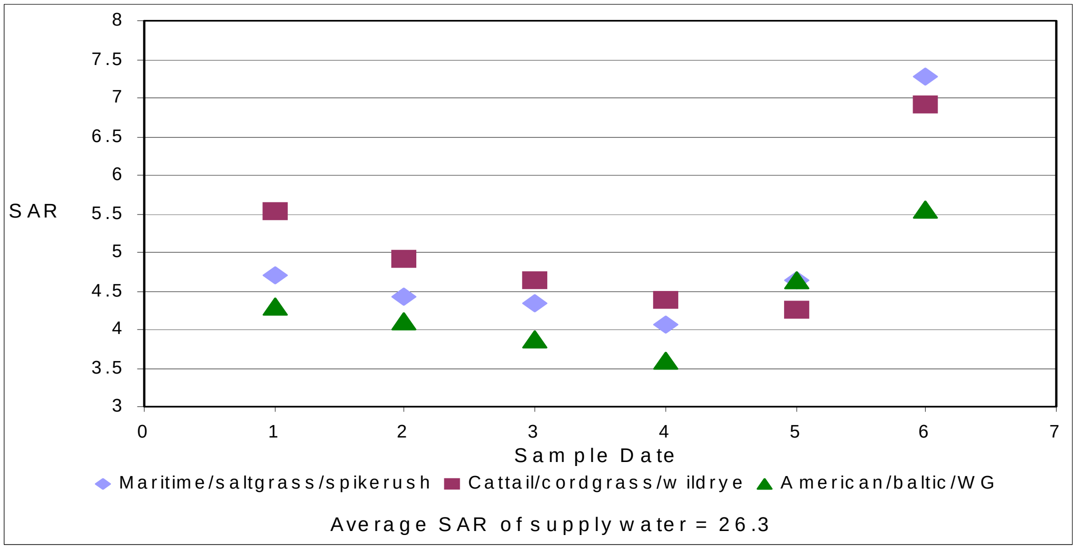

Figure 18. Average groundwater SAR for each community from March - September 2004. Average SAR of supply water was 26.3

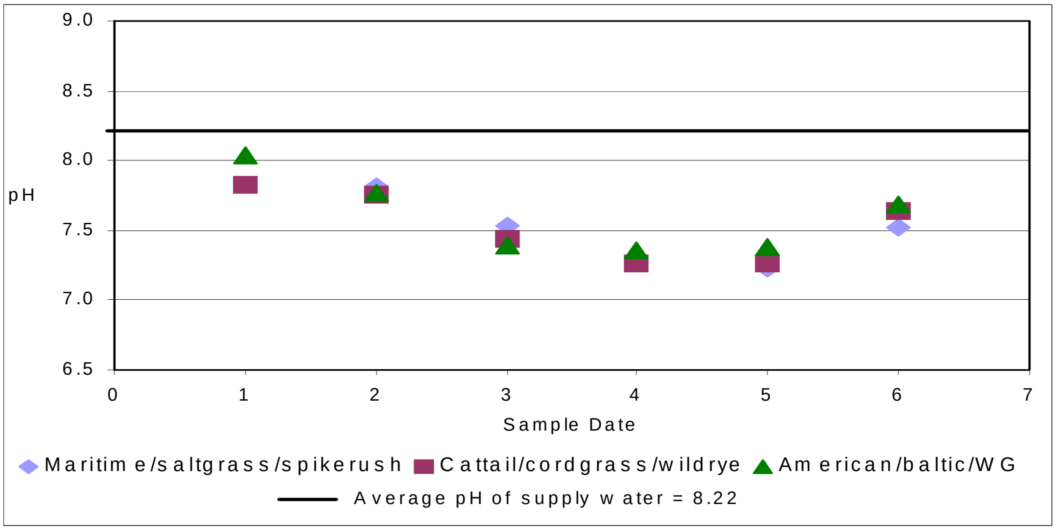

Figure 19. Average groundwater pH for each community from March - September 2004. Average pH of supply water (8.22) represented by the solid line.

Some of the salts in the applied water will be adsorbed onto the soil matrix, and this is illustrated by the overall increase in soil solution EC from saturated paste extracts seen in Figure 20. Figure 20 shows average soil solution EC from saturated paste extract (dS/m) for each region of each community in September 2004. The solid black line represents baseline soil solution EC from saturated paste extract of 0.93 dS/m, while the dashed line represents the average EC of supply water of 3.39 dS/m.

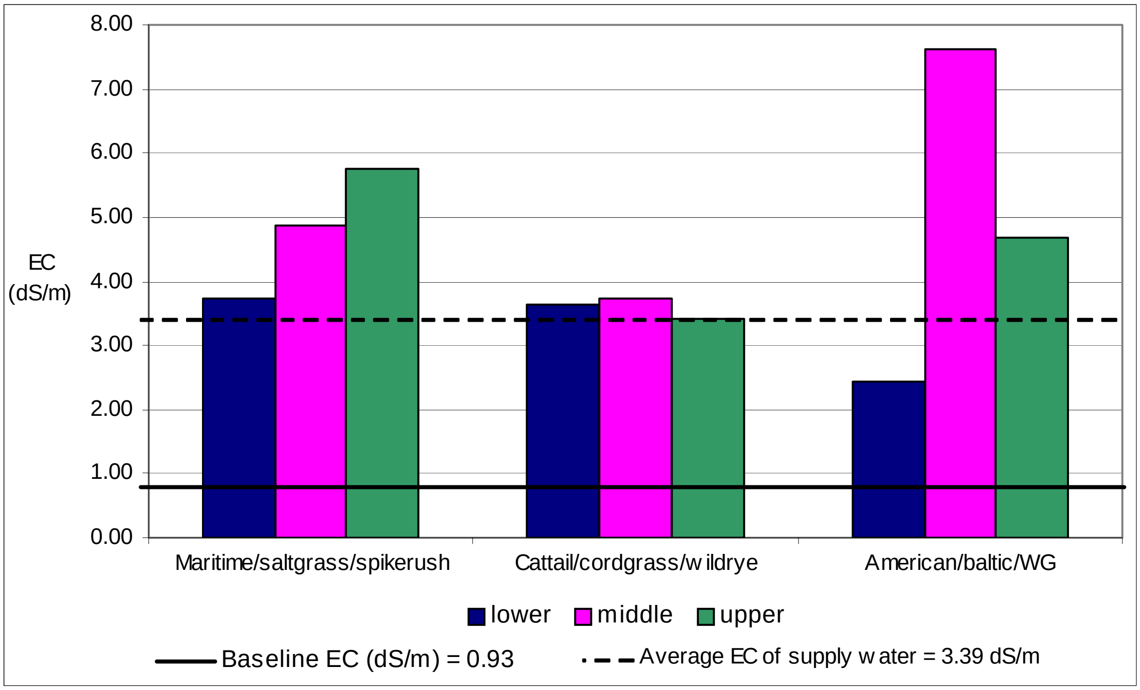

Figure 20. Average soil solution EC (dS/m) from saturated paste extract for each region of each community in September 2004. Baseline soil solution EC (0.93 dS/m) from saturated paste extract represented by the solid line. Average EC of supply water (3.39 dS/m) represented by the dashed line.

Figure 21 is a graph of average soil solution SAR determined from extractable cation concentrations (saturated paste extract) for each region of each community in September 2004. The solid black line represents baseline saturated paste extract SAR of 1.31, while the dashed line represents average supply water SAR of 26.3.

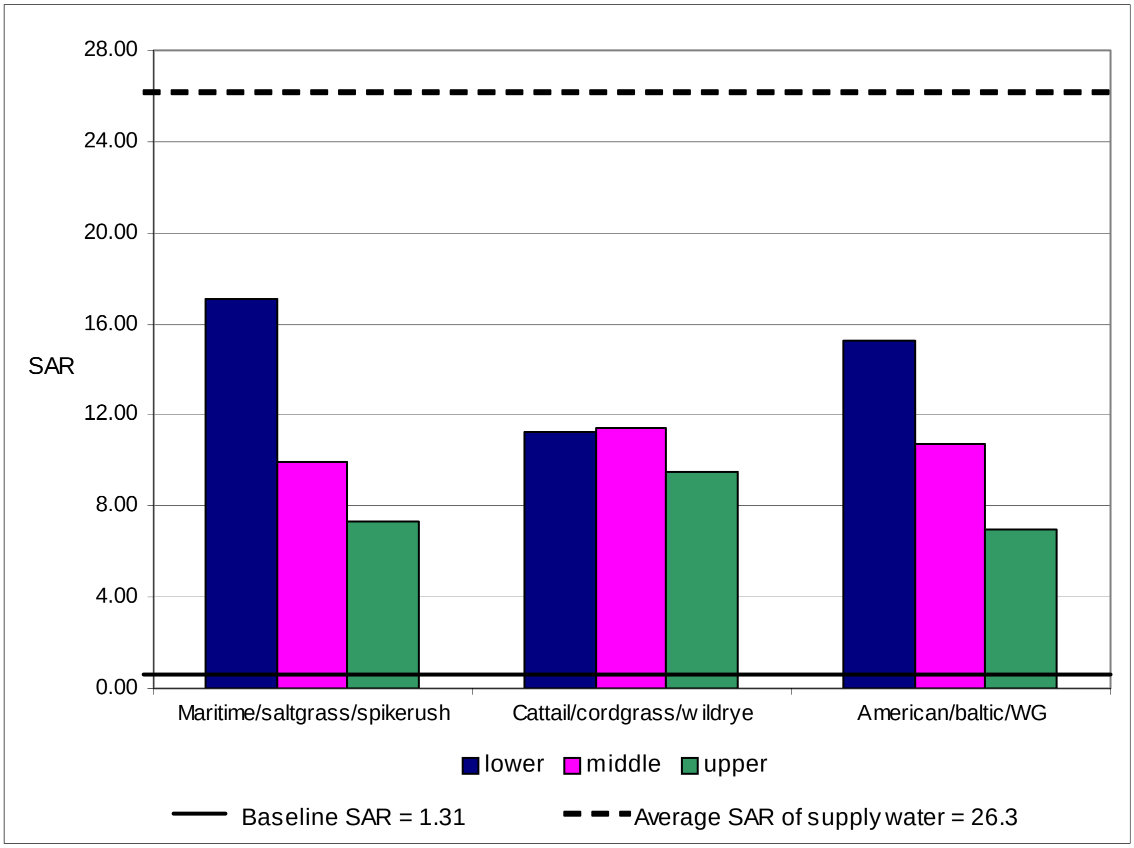

Figure 21. Average soil solution SAR from saturated paste extract for each region of each community in September 2004. Baseline soil solution SAR (1.31) from saturated paste extract represented by the solid line. Average SAR of supply water (26.3) represented by the dashed line.

DISCUSSION AND CONCLUSIONS

Discussion

Due to inherent differences in plant species behavior and physiology one would expect to see significant differences in total water use, but in this study, total water use was not significantly different among communities. Two species in this study did not survive the winter or were out-competed by other, more aggressive species. Insufficient time for communities to establish, as well as a lack of mature plants or full canopies could explain the lack of significant differences in total water use among communities.

Results of plant community water use in this study are contrary to what have been documented for agricultural crops (USDI-BOR, 2004). For purposes of discussion, water use was expressed in terms of equivalent depth of water used in centimeters during the course of this study. Crop water use for 2004 at the Bozeman Agrimet station was as low as 43.4 cm for spring grain, and as high as 80.5 cm for hay alfalfa (USDI-BOR, 2004). Crop water use for this study ranged from 46.4 cm for the American/baltic/WG community to 54.6 cm for the Cattail/cordgrass/wildrye community. Wetland communities in this study had water use similar to that of spring grain even though the wetland communities had an unlimited supply of water. Overall, crop water use for this study was at the lower range of reported values for the Bozeman Agrimet station.

A variety of reasons can be advanced to help explain differences in water use among wetland communities of this study and agricultural crops.

- Some plant communities did not have full vegetative canopies due to species mortality and lack of colonization.

- Relative humidity under the canopy may have been higher than that of the Agrimet station, lowering evaporation, plant transpiration and total water use.
- This study calculated total water use for a community of species while Agrimet stations report water use of individual species.
- An artificial season length was imposed in this study and Agrimet data is from crops which were allowed to senesce under natural conditions.
- Lysimeters were planted in late summer 2003 with perennial species, and plant communities were likely still establishing during the 2004 growing season.
- There was not a significant magnitude of stress placed on plants to allow for species to perform at capacity.
- There may have been measurement differences between the Agrimet station and this study.

Plant Performance and Water Use

Field observations on individual species behavior and performance were recorded throughout the duration of this study. All twelve lysimeters were planted with starts of each species (10T plugs) in the summer of 2003 and irrigated with well water to aid in establishment. Irrigation with simulated CBM product water began once the first plants broke dormancy in March of 2004.

Maritime bulrush was slow to establish when planted in 2003 but in 2004, spring regrowth was robust and by July this species appeared to be healthy and well established. Inland saltgrass was fairly well established and seemed healthy by seasons end in 2003. In all replications, this species either did not survive the winter or, before it had a chance to initiate spring regrowth, was crowded out by Creeping spikerush. In late May, several plants in each replication were observed but Creeping spikerush had already colonized all available bare ground. Creeping spikerush was very well established by the end of 2003 and was one of the first to initiate spring regrowth. Creeping spikerush has higher rates of vegetative spread and earlier spring regrowth than Inland saltgrass. These two characteristics are possible reasons why Creeping spikerush was able to out-compete Inland saltgrass. This species was very aggressive and colonized every region of every replication by mid-summer.

Common cattail was quick to establish in 2003 and slow to start in 2004, but by June, temperatures were increasing and cattails began rapid growth. By the end of this study cattails had colonized the lower end of each lysimeter and appeared to be healthy and vigorous. Prairie cordgrass was slow to establish in 2003 but it survived the winter in all replications. Spring regrowth and colonization were slower than other species, but by September of 2004, Prairie cordgrass seemed well-established and healthy. Canada wildrye was slower to establish in the fall of 2003, but the first to green up in the spring of 2004. This species had rapid early growth, was the first to start seed production, and by August was ready for harvest. Wildrye had very rapid growth and never showed signs of stress such as yellowing or wilting.

American bulrush was quick to establish large root mats in 2003, and seemed to be very well established by the end of 2003, but by spring of 2004 only one or two plants in each replication had survived. Baltic rush was well established in 2003 and in 2004 showed fairly rapid regrowth and colonization, although it never colonized bare ground left by the demise of American bulrush. By the end of the this study Baltic rush was very well established and showed no outward signs of salt or sodium stress. After planting, Streambank wheatgrass did not look as though it would survive the winter, but it was the second species to begin spring regrowth. Although this species did not have rapid vegetative spread it appeared to thrive and by September of 2004 was well-established in all replications.

Although differences in water use were not statistically significant, a comparison of mean values offers some insight to community performance. The American/baltic/WG community had the least crop water use, while the Maritime/saltgrass/spikerush and Cattail/cordgrass/wildrye communities showed similar crop water use (Figure 12). Differences between the former and two latter communities can be explained by the fact that approximately 1/3 of the American/baltic/WG community was bare soil. This was due to lack of spring regrowth by the American bulrush and insufficient colonization of subsequent bare ground by Baltic rush and Streambank wheatgrass. Hence, there was less overall vegetation in the American/baltic/WG community to evapotranspire water. Had the American bulrush survived and flourished, or had the other species colonized the bare soil, crop water use may have been higher.

In the Maritime/saltgrass/spikerush community, saltgrass, which has slow growth rates, did not overwinter well, was slow to initiate spring regrowth, and was replaced by the more adaptive and aggressive spikerush in every replication. By the end of this study Creeping spikerush had colonized the length of each lysimeter (~3meters). This resulted in total water use closer to that of the Cattail/cordgrass/wildrye community (Figure 12).

Slow spring regrowth of cattails left patches of bare soil in the

Cattail/cordgrass/wildrye community, but this community had the greatest total water use even though the Maritime/saltgrass/spikerush community had the most observed ground cover (Figure 12). Canada wildrye was the first of all species to initiate spring growth. As soon as vegetative growth begins in the spring, plant water consumptive use commences, so species with early spring growth are able to utilize available water earlier.

Creeping spikerush only grows 15 to 20 cm high while Wildrye and Cattails can attain mature heights over 1 meter. Large plants produce more biomass than smaller plants, thereby increasing plant water consumptive use. In this study, taller plants such as cattails and wildrye had more vegetation above the overall plant canopy, where it was exposed to atmosphere. This can lead to higher evapotranspiration rates due to differences in solar radiation, wind and relative humidity above and below the vegetative canopy. Cattails and Canada wildrye grow taller than other species in this study and wildrye had the earliest spring growth. These two traits likely increased water use for this community.

Evaporation from a single Class A evaporation pan was compared to average ET of the three plant communities. Results of this study are consistent with data from Agrimet showing ETr (reference ET from a Class A pan) to be higher than crop ET (USDI-BOR, 2004). In all three instances, pan evaporation exceeded community ET (Figure 15). There was only one replication of the pan so results may not be an accurate reflection of pan evaporation. Comparing Agrimet data of 96.7 cm Etr to 72 cm ETr for this study during the same period, pan data is lower than AGRIMET data. This could be due to positioning of the pan in this study. Recall the pan was placed under the greenhouse canopy where relative humidity may have been increased, and wind speed reduced, resulting in lower evaporation for the pan in this study.

Biomass

Significant differences in biomass production (Table 3, Figure 13) are consistent with data reported by the National Agricultural Statistics Service (NASS) (USDA, 2004). Biomass production for each lysimeter (g/ft^2) was used to estimate field-scale biomass production in tons per acre for comparison to values reported by NASS. Yields of all three communities in this study were lower than values reported for hay alfalfa in Gallatin county or counties in the Powder River Basin. Reported yields for other types of hay in the same counties were also higher than yields for this study, with the exception of the Cattail/cordgrass/wildrye community. One reason for this discrepancy is that reported yields are for annual crops and this study was concerned with perennial communities which take longer to become established and attain maximum biomass production. Other factors in lower yields and lack of variability in yields for the American/baltic/WG and Maritime/saltgrass/spikerush communities could have been insufficient colonization and species mortality.

The American/baltic/WG community had the lowest average biomass production of the three communities (29.68 g/ft^2 or 1.42 tons/acre) (Figure 13). This is a consequence of lack of colonization by the other species in this community when American bulrush did not survive the winter. In the Maritime/saltgrass/spikerush community, Inland saltgrass was slow to start spring regrowth and was crowded out by Creeping spikerush. Although this improved percent cover, average biomass production was still low (32.82 g/ft^2 or 1.57 tons/acre) (Figure 13). Rushes and most grasses are known for hollow, pithy stems which, when combined with the short stature of spikerush, could have resulted in lower dry weights. Even with low spring regrowth of the Cattails, the Cattail/cordgrass/wildrye community had the highest biomass production (56.72 g/ft^2 or 2.72 tons/acre) (Figure 13). Again, this is likely a outcome of plant physiology, survival and colonization as discussed previously.

Water Use Efficiency

The WUE metric is dependent on the units selected for computation. In this study, WUE is defined as grams of dry matter produced per lysimeter, divided by kilograms of water used within the same lysimeter over the growing season, strictly for comparison among the communities of this study (Figure 14). Due to lack of significant differences in water use among the communities, calculated WUE merely reflects biomass divided by a constant (or non-significantly different value) for each community. Hence, the community with the least WUE is a reflection of the community with the least biomass, while the community with the highest WUE produced the most biomass (Figures 13 and 14). Any discussion about differences in WUE would merely reiterate the discussion pertaining to biomass production. In hindsight, one may have been better off to use transpiration ratios instead of WUE as transpiration ratios are a better reflection of plant water use.

Soil and Water Chemistry

For purposes of initial planting and soil sampling determinations, each lysimeter was divided into three equal parts (~1.1m) (Figure 7). Initial baseline soil conditions were determined when lysimeters were filled and planted. Soil samples were collected from random positions within each region of each lysimeter following harvest. The intent of soil sampling was to look for general trends in soil solution EC and SAR of saturated paste extracts from each lysimeter. For the rest of this discussion, all mention of soil EC or SAR will be in reference to soil solution EC or SAR from saturated paste extract.

As water is applied to upper elevations, it moves vertically through the soil profile and laterally along elevational gradients. This resulted in more available water in the lower elevations of each lysimeter in this study. Salts remain in solution and are transported with water, so lower elevations of each lysimeter received more salts as well.

Soluble salts in irrigation water will be retained in the soil profile in the absence of either leaching or good internal drainage. Lysimeters were designed to be closed systems so no dilution from groundwater or leaching occurred. Areas with water tables at or near the surface experience higher rates of evaporation than better drained soils. As a result, salt concentrations in the soil increased.

Soil solution EC increased from the beginning to the end of the growing season in all three communities (Figure 20). Differences in soil solution EC were likely a consequence of evapoconcentration, but there is no consistent pattern among communities with respect to location within the lysimeter and changes in soil solution EC (Figure 20). In a closed system lysimeter such as used in this study, the only way to have greater accumulation of soluble salts in the soil from one end of the lysimeter to the other end of the lysimeter would be if one end had greater evapotranspiration than the other or if one species extracted a greater amount of salt or water from the soil.

In the Maritime/saltgrass/spikerush community the highest average soil EC is associated with Creeping spikerush on the upper (somewhat drier) end of the lysimeters and the lowest average soil EC is associated with the Maritime bulrush at the lower (somewhat wetter) end of the lysimeters (Figure 20). Recall that Inland saltgrass was out-competed by Creeping spikerush, thus the comparison is only between Creeping spikerush and Maritime bulrush. Therefore, either Creeping spikerush had higher transpiration than Maritime bulrush or Maritime bulrush extracted more soluble salt from the soil.

All three species in the Cattail/cordgrass/wildrye community were present and soil EC levels were nearly equal for all three positions, indicating consistent evapotranspiration and/or salt uptake among the three species in this community (Figure 20).

In the American/baltic/WG community, American bulrush died out and the area was not colonized by Baltic rush or Streambank wheatgrass. The lowest average soil EC for this community was associated with the bare ground at the lower end of each lysimeter (Figure 20). This position had the lowest water use which substantiates the idea that more water use results in more salts being left behind in the soil. The slightly higher soil EC in the middle position suggests that Baltic rush either used more water than Streambank wheatgrass or was more effective at excluding salts from the transpiration stream.

Soil SAR results indicate a general inverse relationship with EC, i.e. the highest soil SAR is associated with the lowest soil EC and vice-versa within each treatment (Figure 21). SAR is calculated by dividing the amount of sodium present by the square root of calcium plus magnesium divided by 2.

$$SAR = \frac{Na^{2+}(meq/L)}{\sqrt{(Ca^{2+}(meq/L) + Mg^{2+}(meq/L))/2}} \qquad \text{[Eq.6]}$$

The nature of this calculation causes SAR to increase/decrease disproportionately as concentrations of Ca^{2+}, Mg^{2+} and Na^{2+} change. Once CBM product water is exposed to the atmosphere, calcium and magnesium form carbonate precipitates with available CO_3, and the more soluble sodium remains, causing a slight increase in EC but a major increase in SAR.

The highest soil SAR in the Maritime/saltgrass/spikerush community was associated with Maritime bulrush. This is contrary to the idea that higher water use by Creeping spikerush resulted in more sodium being left in the soil (Figure 21). One possible explanation for this is that Maritime bulrush may preferentially uptake divalent cations from saline water, but this cannot be concluded from the results of this study. Soil SAR levels for the Cattail/cordgrass/wildrye community were relatively equal for all three regions (lower, middle, upper) and mirrored EC levels (Figure 21). Although it is possible that preferential uptake of sodium by Cattails caused a lower soil SAR, data from this study do not verify this. The highest soil SAR for the American/baltic/WG community was under the bare ground, suggesting soil chemical reactions in the absence of plant roots, not water use, may be driving the SAR upward (figure 21).

For this experiment, groundwater was represented by water which percolated through the soil to the gravel layer where it could be sampled. Over the course of the growing season, soil solution and groundwater chemistry changed with respect to EC, SAR and pH (Figures 16, 17, 18 and 19). Evaporation and evapoconcentration through plant water use resulted in a general increase in EC in all twelve replications (Figures16 and 17). In general, groundwater SAR and pH mirrored one another. Both showed a slight decrease in the first three months of the study, and by the end of the study both had increased, although SAR showed a greater increase than pH (Figures 18 and 19). This could be a result of changes in pH. As pH decreases, calcium solubility increases causing a decrease in SAR due to the presence of more calcium in the system.

Conclusions

Evapoconcentration of salts in a constructed wetland could lead to adverse soil salinity and sodicity conditions with respect to long-term impoundment, species viability and reclamation. Over time, increasing salinity and sodicity may have detrimental effects on plant propagation, seedling emergence, establishment and yields as well as increasing plant mortality. Native range plants of the Powder River Basin have some tolerance to salinity due to the nature of soils in the area, but may not be able to re-establish on previously constructed wetland sites with significantly elevated salinity and sodicity.

Results of this study indicate that although native wetland plant communities have potential to utilize saline-sodic water while remaining viable, no one community stood out in terms of total water use. An initial comparison of pan evaporation to community ET suggests a free water surface associated with lined ponds would appear to provide a more efficient means for reducing the volume of produced water associated with CBM development. For example, based on data from this study, a one-acre constructed wetland with seasonal water use of 59 cm (Maritime/saltgrass/spikerush community), could evapotranspire 1.77 acre feet of water during a single growing season, while a one-acre lined pond with seasonal water use of 72 cm (pan evaporation) could potentially evaporate approximately 2.16 acre feet of water. Not a very large difference when one considers that constructed wetlands have potential to be more visually appealing than evaporation ponds while increasing recreation opportunities such as hunting and fishing. Constructed wetlands also have the added benefit of providing food and habitat for wildlife, and some plant species have potential to be used as forage.

Based on observed behavior, colonization and species robustness, Maritime bulrush, Baltic rush, Creeping spikerush and Canada wildrye appeared to be the most likely candidates from this study for use in a constructed wetland designed for beneficial use of saline-sodic water.

APPENDICES

APPENDIX A

Particle Size Analysis

Appendix A: Summary of particle size analysis of soil samples for 0-15cm and 16-60cm, collected from six soil pits excavated on site from which study soil was obtained. Soil used to fill wetland cells was collected from 16-60cm depth in proximity to and surrounding pits 2 and 3 (highlighted in red). Soil from 0-15cm depth was stockpiled and used for revegetation of excavation site.

SAMPLE #	Pit/sample depth	corrected 40sec[1]	corrected 24hr[1]	SAND g/100g[2]	CLAY g/100g[2]	Textural Class
1	Pit 1 0-15cm	24.5	14.5	50	29	Sandy Clay Loam
2	Pit 1 16-60cm	22	13	56	26	Sandy Clay Loam
3	Pit 2 0-15cm	25	14.5	50	29	Sandy Clay Loam
4	Pit 2 16-60cm	30.5	21	39	42	Clay
5	Pit 3 0-15cm	29	17.5	42	35	Clay loam
6	Pit 3 16-60cm	32.5	20.5	35	41	Clay
7	Pit 4 0-15cm	28	16	44	32	Clay loam
8	Pit 4 16-60cm	31	18	38	36	Clay loam
9	Pit 5 0-15cm	28.5	15.5	43	31	Clay loam
10	Pit 5 16-60cm	32	19	36	38	Clay loam
11	Pit 6 0-15cm	25.5	12	49	24	Loam
12	Pit 6 16-60cm	28.5	18	43	36	Clay loam

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[1] Corrected values are actual readings minus the hydrometer reading of a blank solution

[2] Sand defined as >0.05mm diameter; clay defined as <0.002mm diameter (Gee and Bauder, 1986).

APPENDIX B

Plant Characteristics Table

Appendix B: Categorization of selected native species suitability for constructed wetlands - a comprehensive review.

Common Name	Scientific name	Growth habit / Duration	Active growth period	Growth Rate	Propagation Method	pH Range
Alkalai (Maritime) bulrush	*Scirpus maritimus*	Graminoid / Perennial	Spring, Summer	Slow	Rhizomes/Seed	4 - 7
American bulrush	*Scirpus americanus*	Graminoid / Perennial	Summer	Moderate	Rhizomes/Seed	3.7 - 7.5
Common cattail	*Typha latifolia*	Forb-herb / Perennial	Spring, Summer	Rapid	Rhizomes	5.5 - 7.5
Inland saltgrass	*Distichlis spicata*	Graminoid / Perennial	Spring, Summer, Fall	Slow	Rhizomes	6.4 - 10.5
Baltic rush	*Juncus balticus*	Graminoid / Perennial	Spring, Summer	Rapid	Rhizomes/Seed	6 - 9
Prairie cordgrass	*Spartina pectinata*	Graminoid / Perennial	Spring, Summer	Rapid	Rhizomes/Seed	6 - 8.5
Creeping spikerush	*Eleocharis palustris*	Graminoid / Perennial	Spring	Moderate	Rhizomes/Seed	4 -8
Streambank wheatgrass	*Pascopyrum smithii*	Graminoid / Perennial	Spring, Summer, Fall	Moderate to Rapid	Rhizomes/Seed	4.5 - 9
Canada wildrye	*Elymus canadensis*	Graminoid / Perennial	Spring, Summer, Fall	Rapid	Tillers/Seed	5 - 7.9

Table References:

Uchytil, 1990; Snyder, 1992a; Snyder, 1992b; Uchytil, 1992a; Uchytil, 1992b; Hoag, 1998a; Hoag,1998b; Hoag, 1998c; Hoag, 1998d; Simonin, 2000; Hoag et al., 2001; USDA-NRCS, 2004; Prairie Seeds, 2004.

Appendix B (Cont): Categorization of selected native species suitability for constructed wetlands - a comprehensive review.

Common Name	Lysimeter Position	Wetland Indicator Status [A]	Pioneer	Competitive	Nitrogen Fixer	C:N Ratio [B]	Root Depth	Root Matrix
Alkalai (Maritime) bulrush	Lower	OBL	Yes	No	No	High	12"	Yes
American bulrush	Lower	FAC, FACW	Yes	Yes	No	Med	14"	Yes
Common cattail	Lower	OBL	Yes	Very	No	High	14"	Yes
Inland saltgrass	Middle	FAC, FACW	Yes	No	No	High	2"	Yes
Baltic rush	Middle	FACW, OBL	Yes	No	Yes*	Med	20"	Yes
Prairie cordgrass	Middle	FACW, OBL	Yes	No	No	High	18"	N/A
Creeping spikerush	Upper	OBL	Yes	No	Yes*	High	14"	Yes
Streambank wheatgrass	Upper	N/A	Yes	No	No	Med	20"	Yes
Canada wildrye	Upper	FACU, FAC	Yes	No	No	Med	16"	No

Explanation of symbols used in this table:

A - Wetland Indicator Status - See Table 2. USDA-NRCS. 2004.

B - Carbon to nitrogen ratio. USDA-NRCS. 2004.

C:N >12 slow decomposition and accumulation. C:N <12 rapid decomposition and accumulation.

* - Reported in PLANTS Database, USDA-NRCS, 2004.

Appendix B (Cont): Categorization of selected native species suitability for constructed wetlands - a comprehensive review.

Common Name	Salinity Tolerance [C]	Anaerobic Tolerance [D]	Drought Tolerance [E]	Moisture Use	Soil adaptation fine/med/coarse	Sustainability Fresh/saline/brackish
Alkalai (Maritime) bulrush	High 77 dS/m*	High	Low	Moderate	ALL	Fresh/saline/brackish
American bulrush	High 42.5 dS/m*	High	Mod-high	Moderate	Fine/Medium	Fresh/saline/brackish
Common cattail	Low-High 17.5 dS/m*	High	None	High	ALL	Fresh/slightly brackish
Inland saltgrass	High 70 dS/m*	High	Moderate	Moderate	Fine/Medium	Fresh/saline/brackish
Baltic rush	High	High	Low	High	ALL	Fresh/slightly saline
Creeping spikerush	Low	High	Low	High	Medium/Coarse	Fresh/slightly saline
Prairie cordgrass	None	High	Low	High	Fine/Coarse	Fresh/slightly saline
Streambank wheatgrass	High 34 dS/m*	Moderate	Moderate to high	Moderate	Medium/Coarse	Fresh/slightly saline
Canada wildrye	Moderate	None	Moderate	Moderate	ALL	Fresh/slightly saline

Explanation of symbols used in this table:

C - Salinity tolerance - Low < 4 dS/m, Mod 4 - 9 dS/m, High > 9 dS/m (Brady and Weil, 1999). USDA-NRCS, 2004.
*From Aronson, 1989.
D - Anaerobic tolerance - USDA-NRCS. 2004.
E - Drought tolerance - USDA-NRCS. 2004.

Appendix B (Cont): Categorization of selected native species suitability for constructed wetlands - a comprehensive review.

Common Name	Forage Quality [F]	Grazing Preference	Resistance to grazing/trampling	Conservation Uses
Alkalai (Maritime) bulrush	Low	Livestock will consume young plants	N/A	Erosion control, wastewater treatment, creation/restoration of wetlands, bank stabilization
American bulrush	Low	Livestock, wildlife - early season	Yes	Erosion control, wastewater treatment, creation/restoration of wetlands, bank stabilization
Common cattail	Low	Waterfowl, muskrats	Will tolerate moderate grazing	Highly invasive-not used for conservation
Inland saltgrass	Fair	Livestock, wildlife	Yes	Good for reclamation of saline sites
Baltic rush	Low to very good	Hay crop for cattle. Forage for livestock and elk	Will increase with heavy grazing	Erosion control, wastewater treatment, creation/restoration of wetlands, bank stabilization
Creeping spikerush	Med-high in Spring	Livestock, big game, ducks, geese	Yes	Erosion control, creation/restoration of wetlands, bank stabilization, sediment trap
Prairie cordgrass	Low	Muskrats, livestock waterfowl	Will tolerate moderate trampling	Erosion control, creation/restoration of wetlands, stabilization, species diversity
Streambank wheatgrass	High in spring	Livestock, big game	Moderate sod formation	Erosion control, reclamation, stabilization
Canada wildrye	Med	Livestock, wildlife	Yes, short-lived	Restoration, erosion control - plants live 2-4 yrs

Explanation of symbols used in this table:

F - Forage quality - Based on crude protein content. USDA-NRCS. 2004.

APPENDIX C

Selected Plant Species Descriptions

Appendix C: Selected Plant Species Descriptions

Maritime or Alkali bulrush (*Scirpus maritimus*) is a heavily rhizomatous, native perennial wetland plant found in areas with saturated soils or standing water up to 1 meter deep (Hoag, 1998b; Hoag et al., 2001; USDA-NRCS, 2004). It propagates best when the water table is within 10 cm of the surface (Hoag, 1998b; USDA-NRCS, 2004). Alkali bulrush typically occurs on freshwater sites, but will also form large, dense stands in either alkaline or saline sites, preferring a pH range of four to seven but tolerating values up to nine (Hoag, 1998b; USDA-NRCS, 2004). It is a pioneering species and is usually replaced by other species under good soil and water conditions (Hoag et al., 2001). Mandel and Koch (1992) reported that the large carbon reserves of Alkali bulrush maintain carbohydrate levels through metabolic conservation, and are not affected when under anoxia stress. Alkali bulrush is an excellent choice for wastewater treatment as the rhizomes form a matrix for beneficial bacteria (Mandel and Koch, 1992; USDA-NRCS, 2004). When alkali bulrush is grown at or above the water surface it produces fewer seeds, but has better shoot survivorship, and produces a greater number of tillers, thereby increasing production of underground biomass (Mandel and Koch, 1992; Kantrud, 1996). If it is grown in deeper water it produces a greater number of seeds, but less underground biomass, tillers, and total biomass (Mandel and Koch, 1992). Seeds and rhizomes are food for waterfowl, game birds and songbirds as well as muskrat and beaver (Hoag, 1998b; Hoag et al., 2001; USDA-NRCS, 2004). Reports on use by grazers vary; Kantrud (1996) states that cattle and horses readily graze the young plants while others say grazers rarely use this species (Hoag, 1998b; Hoag et al., 2001; USDA-NRCS, 2004).

Inland saltgrass (*Distichlis spicata*) is a highly salt tolerant, native perennial common in sloping and flood channel bank configurations in drainage systems of Wyoming and the western United States (Uchytil, 1990; USDA-NRCS, 2004). Growth is rapid with plants spreading via a well-developed system of deep underground rhizomes (Uchytil, 1990; USDA-NRCS, 2004). Inland saltgrass has moderate water use rates, and water tables are often at or near the surface (Uchytil, 1990; USDA-NRCS, 2004). Inland saltgrass can withstand anaerobic conditions, and rhizomes will sprout even when covered by 30cm of sediment (Uchytil, 1990). The lacunae tissue of the roots is apparently continuous with the rhizome and leaf sheath which allows for gas exchange under partial inundation and in heavy soils (Uchytil, 1990). It tolerates slightly acidic to highly alkaline pH values (6.4 - 10.5), (USDA-NRCS, 2004). Inland saltgrass is highly salt tolerant, persisting in EC values up to 70 dS/m (56,000 ppm) (Ungar, 1974). Salt glands are active in the extrusion of salt, which helps maintain adequate osmotic potentials (Uchytil, 1990). Vesicular-abuscular mycorrhizal fungi have been observed on inland saltgrass roots and are thought to further enhance salt tolerance (Uchytil, 1990). It is a pioneer species, colonizing barren, saline soils with the aid of sharp, pointed rhizomes which are well adapted to piercing heavy clays and shales, effectively loosening hard packed soil. The ability of Inland saltgrass to loosen hard packed soil may help other plants become established (Uchytil, 1990; USDA-NRCS, 2004). Inland saltgrass provides fair forage for cattle and horses because it remains green during periods of drought when most other grasses are dry; ducks are reported to occasionally eat the dried seeds and burning provides tender forage for wild geese (Uchytil, 1990;

USDA-NRCS, 2004).

Creeping spikerush (*Eleocharis palustris*) is a native perennial hemicryptophyte that grows along marshes, ditches and streambanks, and in lakeshores, river bottoms, wet meadows and flood areas (Snyder, 1992a; Hoag, 1998d; Hoag et al., 2001; USDA-NRCS, 2004). Reproduction is rhizomatous with rapid vegetative spread, and rhizomes will spread into areas too deep for seedling establishment (Snyder, 1992a; Hoag, 1998d). Creeping spikerush develops a thick root mass that can extend 40+ cm in the soil profile, giving it the ability to resist erosion and compaction, and survive in areas where the water table drops to below 30cm of the surface (USDA-NRCS, 2004). It has high water use rates and will tolerate standing water up to 15 cm deep and three to four months of flooding (Hoag et al., 2001; USDA-NRCS, 2004). Creeping spikerush has a low salinity tolerance, and the optimum pH range is 4 - 8 (USDA-NRCS, 2004). It is a nitrogen fixer, and through recycling, makes nitrogen available to other plants in the wetland (Snyder, 1992a; Hoag et al., 2001). The seeds and rhizomes are food for ducks and geese while rabbits, muskrats, big game and other grazers utilize it for its high spring protein content (Hoag, 1998d; Hoag et al., 2001; USDA-NRCS, 2004).

Common cattail (*Typha latifolia*) is a native perennial that reproduces by seed dispersal and rapid vegetative propagation from rhizomes (Lorenzen et al., 2000; USDA-NRCS, 2004). Preferred habitats are marshes and pond edges with season-long saturated soils, and/or standing or slow moving water up to 30 cm deep (Allen et al., 1992; Uchytil, 1992b; Hoag et al., 2001; USDA-NRCS, 2004). Reports on salinity tolerance vary widely (Uchytil, 1992b; Hoag et al., 2001; USDA-NRCS, 2004) but, in general, cattails have moderate to high salinity tolerance. Cattails have high water use rates, and can withstand perennial flooding and reduced soil conditions (Allen et al., 1992; Hoag et al., 2001). At the appropriate stage of growth, all parts of the cattail are edible, but forage quality is only high in early spring for livestock and big game and by summer it is a poor protein and energy source (Uchytil, 1992b; USDA-NRCS, 2004).

Prairie cordgrass (*Spartina pectinata*) is a native, rhizomatous species found in a variety of habitats from low-lying roadsides, marshes, streams and flood plains to seasonally dry sites (Hoag et al., 2001; USDA-NRCS, 2004). Two very noticeable features of prairie cordgrass are the presence of aggressive rhizomes, which have the ability to grow 2.5 - 3.5 meters per year and a dense, deep root system with root biomasses up to 3000 g/m^2 (USDA-NRCS, 2004). Although it is typically a freshwater species, it will tolerate moderate salinity and alkaline conditions (Hoag et al., 2001; USDA-NRCS, 2004). It has high water use rates, can grow streamside in 0.3 m of water, and will tolerate extensive temporary flooding, high water tables and occasional drought (Walkup, 1991). The seeds and rhizomes are food for small mammals, and waterfowl (Hoag et al., 2001). Reports on forage quality are contradictory; Hoag et al. (2001) states that the plants provide high quality forage for muskrats, geese, livestock and other grazers, while the USDA-NRCS (2004) states that it is not a forage resource.

Canada wildrye (*Elymus canadensis*) is a native cool-season bunchgrass inhabiting disturbed sites from riparian areas to wetlands (Simonin, 2000; Prairie Seeds, 2004; USDA-NRCS, 2004). It is typically found along incised channel banks of ephemeral streams in north-central Wyoming, and along the Missouri River flood plain in

Montana (Simonin, 2000). Canada wildrye tolerates a range of hydrological regimes, showing fair to good flood tolerance and moderate water use rates (Prairie Seeds, 2004; USDA-NRCS, 2004). It is a quick starter, and can be prolific from seeds or tillers (Simonin, 2000). It has been noted to be fairly salt tolerant and prefers neutral to alkaline pH (Simonin, 2000; USDA-NRCS, 2004). Canada wildrye provides good early season forage, and good fall regrowth for late-fall and spring forage, but once mature is generally considered inferior (Prairie Seeds, 2004; USDA-NRCS, 2004).

American bulrush (*Schoenoplectus americanus*) is a native perennial, commonly found in backwater areas of streams, lakes, ponds, swamps, wet woods and roadside ditches (Mandel and Koch, 1992; Hoag, 1998a; Hoag et al., 2001; USDA-NRCS, 2004). It has a robust root system, with medium to rapid rates of rhizomatous spread. American bulrush is an obligatory wetland plant which tolerates freshwater, alkaline and saline conditions, and is reported as surviving in brackish waters with EC values of 42.5 dS/m (Uchytil, 1992a). Although it prefers a neutral pH, it can tolerate pH values up to 8.9 (Mandel and Koch, 1992). American bulrush will endure long periods of drought or water levels 5 - 10 cm above the surface for 3 - 4 weeks but growth is inhibited in greater than 60 cm of water (USDA-NRCS, 2004). Seeds and rhizomes of the plant provide food for muskrats, geese and other waterfowl, and grazers will use it for forage in early growth stages but palatability and production are low (Uchytil, 1992a).

Baltic rush (*Juncus balticus*) is the most common and widespread rush in the dry Intermountain and Great Basin regions (Snyder, 1992b; Hoag, 1998c; Hoag et al., 2001). It is a rhizomatous, native perennial found from low elevations to subalpine and alpine sites (Snyder, 1992b; Hoag, 1998c; Hoag et al., 2001; USDA-NRCS, 2004). Typical habitats are wet depressions, marshes, springs and pond or stream edges. Favored environmental conditions are areas which are flooded in spring and dry out in the fall (Hoag, 1998c). *Juncus* species can tolerate a wide range of hydrologic conditions, from severe drought with water tables 3 m or more below soil surface to extreme flooding (Hoag et al., 2001). Baltic rush is found in a wide range of soil types as well, from acidic to neutral, alkaline or sodic (Hoag, 1998c). Baltic rush is an important part of the nutrient dynamics of wetland plants communities because of its ability to fix nitrogen (Hoag, 1998c). It is resistant to erosion and trampling because of dense root systems (Snyder, 1992b), which also form a matrix for beneficial bacteria (USDA-NRCS, 2004). Baltic rush is an important forage species for livestock and elk, and is used as hay for cattle, although palatability decreases as the season progresses (Snyder, 1992b; Hoag et al., 2001). Seeds and rhizomes are food for small mammals, waterfowl and upland game birds, while the plants provide important cover (Hoag et al., 2001).

Streambank wheatgrass (*Elymus lanceolatus*) is a native perennial sod-forming grass (USDA-NRCS, 2004). It has an extensive rhizomatous root system, and vegetative propagation occurs primarily by rhizomes (USDA-NRCS, 2004). Streambank wheatgrass is found in slightly acidic to moderately saline conditions. It will tolerate moderate flooding and has high drought tolerance, but prefers seasonally saturated upland or terrace soils (USDA-NRCS, 2004). Streambank wheatgrass provides good early season forage for livestock and wildlife until fall when the plant dries out and becomes coarse (USDA-NRCS, 2004).

APPENDIX D

Simulated CBM Product Water

Appendix D. Simulated CBM Product Water.

Volume water (Liters)	Sodium Bicarbonate (NaHCO3) (g)	Sodium Chloride (NaCl) (g)	EC dS/m	pH	SAR
1L	1.4	0.6	~ 3.18	~ 8.38	~ 22.011657
110	154	66	~ 3.18	~ 8.38	~ 22.011657
750	1050	450	~ 3.18	~ 8.38	~ 22.011657
946.4	1324.96	567.84	~ 3.18	~ 8.38	~ 22.011657
1135.6	1589.84	681.36	~ 3.18	~ 8.38	~ 22.011657
1365	1911	819	~ 3.18	~ 8.38	~ 22.011657

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