Effects of irrigation water quality and water table position on plant biomass production, crude protein, and base cation removal
by Shannon Dale Phelps

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

Abstract:
This research examines the effects of surface irrigation water quality and water table position on the ability of selected plant species to produce biomass and crude protein, and to remove the base cations sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) from shallow groundwater. It was hypothesized that selected plant species could effectively produce biomass and crude protein, and potentially remove salts from shallow groundwater. Columns were arranged in the greenhouse as a two water quality x three water table positions x three plant species randomized complete block experiment. Water qualities were simulated coalbed methane product water (treatment) and simulated Powder River water (control). Three water table positions were maintained at 114, 76, and 38 centimeters from the column soil surface. Wytana saltbush (Atriplex wytana), Big saltbrush (Atriplex lentiformis) and Maritime barley (Hordeum marinium) were selected for their livestock forage and salt tolerant (halophytic) characteristics. Columns irrigated with simulated coalbed methane water had higher electrical conductivity (EC) and sodium adsorption ratio (SAR) than those irrigated with simulated Powder River water. Mean EC and SAR increased linearly with time at all water table positions in both the control and treatment. EC and SAR increased the fastest in columns maintained at the 38 cm or shallowest water table position. Column EC and SAR did not increase at the same rate over time due to differences in soil surface evaporation, plant water use, and the preferential removal of calcium (Ca^{+2}) from shallow groundwater. Hordeum marinium produced more biomass, but did not contain the quality of crude protein found in the Atriplex species. Atriplex lentiformis produced the highest quality forage. Plant species responded to water table position more than water quality. Both Atriplex species produced the most biomass at the 38 cm water table position, while Hordeum marinium produced the most biomass at the 76 cm water table position. Atriplex lentiformis removed more sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) than Hordeum marinium and Atriplex wytana at all water table positions in both the simulated Powder River and coalbed methane water treatments.

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Shannon Dale Phelps

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

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ABSTRACT

This research examines the effects of surface irrigation water quality and water table position on the ability of selected plant species to produce biomass and crude protein, and to remove the base cations sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) from shallow groundwater. It was hypothesized that selected plant species could effectively produce biomass and crude protein, and potentially remove salts from shallow groundwater. Columns were arranged in the greenhouse as a two water quality x three water table positions x three plant species randomized complete block experiment. Water qualities were simulated coalbed methane product water (treatment) and simulated Powder River water (control). Three water table positions were maintained at 114, 76, and 38 centimeters from the column soil surface. Wytana saltbush (*Atriplex wytana),* Big saltbrush (*Atriplex lentiformis*) and Maritime barley (*Hordeum marinium*) were selected for their livestock forage and salt tolerant (halophytic) characteristics. Columns irrigated with simulated coalbed methane water had higher electrical conductivity (EC) and sodium adsorption ratio (SAR) than those irrigated with simulated Powder River water. Mean EC and SAR increased linearly with time at all water table positions in both the control and treatment. EC and SAR increased the fastest in columns maintained at the 38 cm or shallowest water table position. Column EC and SAR did not increase at the same rate over time due to differences in soil surface evaporation, plant water use, and the preferential removal of calcium (Ca^{+2}) from shallow groundwater. *Hordeum marinium* produced more biomass, but did not contain the quality of crude protein found in the *Atriplex* species. *Atriplex lentiformis* produced the highest quality forage. Plant species responded to water table position more than water quality. Both *Atriplex* species produced the most biomass at the 38 cm water table position, while *Hordeum marinium* produced the most biomass at the 76 cm water table position. *Atriplex lentiformis* removed more sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) than *Hordeum marinium* and *Atriplex wytana* at all water table positions in both the simulated Powder River and coalbed methane water treatments.

1. INTRODUCTION

Exploration, development, and production within the coalbed methane (CBM) gas industry have increased dramatically over the past ten years. Since 1997, the Powder River Basin in Wyoming and Montana has emerged as one of the most active new areas of CBM production in the U.S., comprising nearly 7.5% of U.S. total natural gas production (Rice *et al.*, 2001). The Powder River Basin is the primary watershed for the Powder River. The Powder River and its tributaries drain an area of approximately 34,700 square kilometers and run north from northeastern Wyoming to southeastern Montana (Hembree *et al.*, 1952) (Figure 1).

CBM extraction is unconventional in that wastewater is produced during the extraction process. In a conventional oil and gas reservoir, the gas lies atop the oil, which, in turn, lies atop the water. An oil or gas well draws only from the petroleum reservoir without extracting a large volume of water. However with CBM reservoirs, water permeates the coal beds and its pressure traps methane within the coal (Rice, 1997). This results in the inability of CBM extraction without the concurrent extraction of water from within the confined coal seam.

Most data on CBM waters have been gathered at two historically large production areas: the San Juan Basin in Colorado and New Mexico and the Black Warrior Basin in Alabama. Rapid development in basins with limited data on CBM water, like the Powder River drainage, are currently a concern of producers, landowners, Federal, State, and local agencies, coalmine companies, and Native Americans (Rice, 1999).

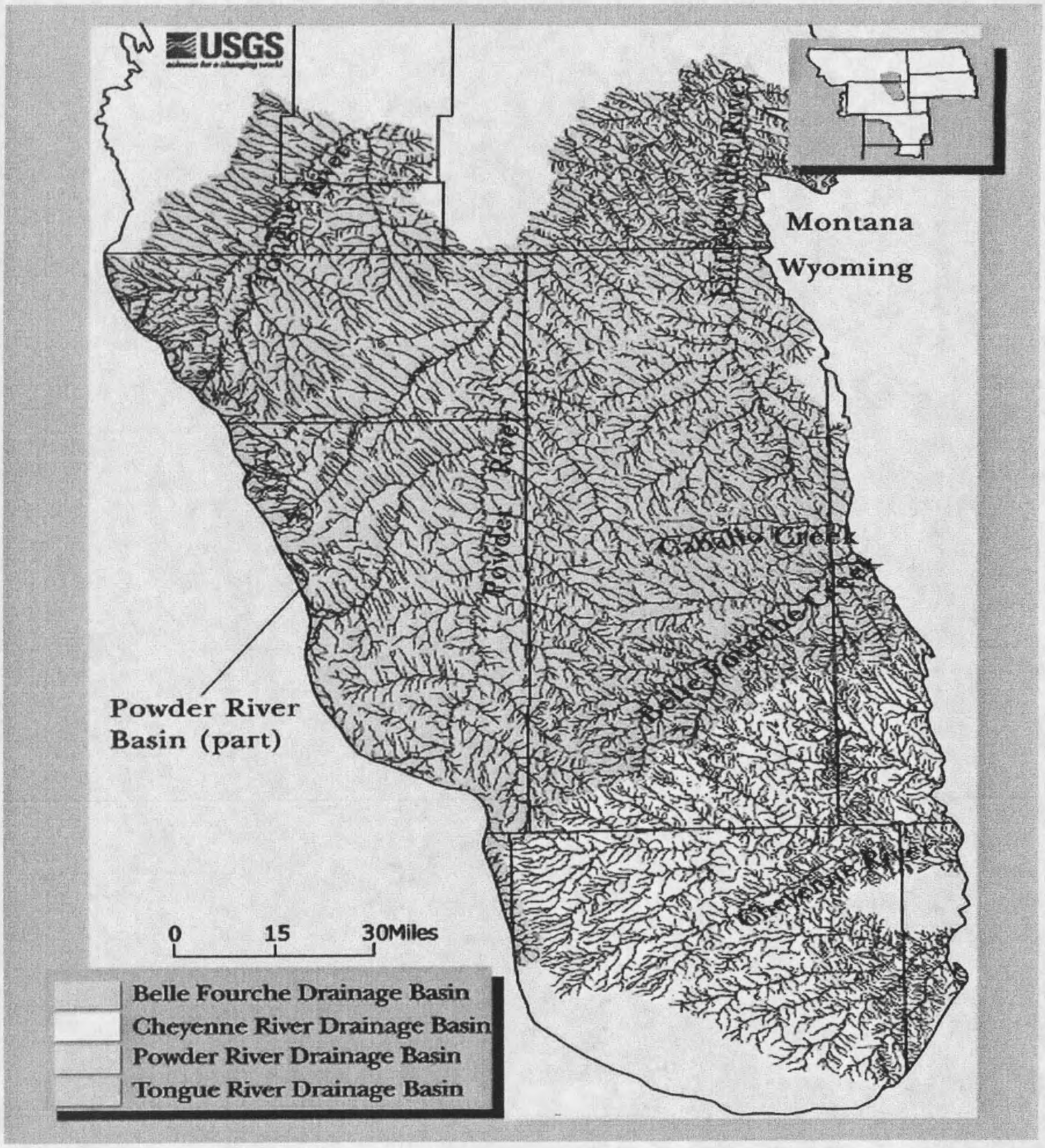

Figure 1. Map of drainage basins in Montana and Wyoming (map provided by U.S. Geological Survey, 2001).

This research examines the effects of surface irrigation water quality and water table position on selected plant species' abilities to produce biomass and crude protein and to remove the base cations sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) from shallow groundwater. It was hypothesized that selected species could effectively produce biomass and crude protein, and potentially phytoremediate saline-sodic irrigation water by reducing the sodicity and salinity of that water.

The objectives of this study were:

1. to compare the effects of irrigation with simulated CBM (treatment) and simulated Powder River (control) water on shallow groundwater chemistry;
2. to compare the effects of shallow water table positions on shallow groundwater chemistry and plant production; and,
3. to evaluate selected plant species' abilities to produce biomass and crude protein and to remove sodium (Na^{+1}), calcium (Ca^{+2}), and magnesium (Mg^{+2}) from shallow groundwater over a 32-week period of study.

2. LITERATURE REVIEW

Properties of Irrigation Water: Sodicity and Salinity

Coalbed methane product water with relatively high concentrations of sodicity and salinity has been recorded from wells in the Powder River drainage (Rice et al., 2001). Generally, dissolved ions in water co-produced with CBM consists mainly of sodium (Na^{+}) and bicarbonate (HCO_3^{-}). The composition of the water is controlled in great part by the association of the waters with a gas phase containing varying amounts of carbon dioxide (CO_2) and methane (CH_4). The bicarbonate component potentially limits the amount of calcium (Ca^{+2}) and magnesium (Mg^{+2}) through the precipitate of carbonates. The sulfide (S^{-2}) is removed as either a gas or a precipitate (Rice et al., 2001).

The sodic hazard of irrigation water is related to the amount of exchangeable sodium compared to the exchangeable calcium and magnesium. The sodium adsorption ratio (SAR) is an effective measure of the potential sodium hazard of water that is in exchange equilibrium with a soil (Hanson et al., 1999). The chemical characteristics of sodium provide it with properties of a dispersing agent in fine textured soils. Excessive sodium, when not balanced with divalent cations, causes soil aggregate structures to disintegrate or disperse (Dollhopf, 2000).

Additionally, sodium can affect crop growth indirectly by causing nutritional imbalances and by degrading the physical structure of the soil. High sodium levels can cause calcium, potassium, and magnesium deficiencies. Moreover, high sodium levels relative to calcium concentrations can severely reduce the rate at which water infiltrates the soil, which can affect the plant because of poor aeration (Hanson et al., 1999).

The soils of the Powder River Basin are primarily made up of silts, clays, silt loams, silty clay loams, clay loams, and sandy clays (U. S. Department of Agriculture, 1971). These Powder River soil types have the potential to disperse when they are exposed to high SAR water. In addition, the adverse impacts of sodicity on dispersion of fine-earth soils are exacerbated by arid and semi-arid zone environments where rainfall conditions of significance seldom occur during the irrigation season (Rengasamy and Sumner, 1998).

Salinity has also plagued crop production in irrigated regions of the world since the beginning of recorded history. It is particularly common in arid and semi-arid areas where evapotranspiration, evaporation of water from soil combined with transpiration of water from plants, exceeds annual precipitation and where irrigation is therefore necessary to meet crop water needs (Hanson et al., 1999). A saline soil or water is one containing enough salts to interfere with the growth of most plant species. This loss in plant productivity is not a phytotoxic response but is the result of osmotic stress (Bauder and Brock, 2001). A saline soil or water occurs when the EC of a saturated extract or water sample is greater than 4 dS/m (U.S. Department of Agriculture, 1979), but salinity exceeding 2 dS/m may limit the growth rate of some plant species.

Salinity has the potential to have significant impacts on plant communities, plant community sustainability, and livestock and wildlife forage capabilities. Without a well draining soil matrix, salinity associated with CBM discharge water may accumulate in the upper soil layers. Under conditions of limited irrigation or precipitation, the leaching of salts below the root zone may not occur and over time the soil may become saline.

According to Maas and Grattan (1998), the most common effect of salinity is a general stunting of growth. The result is a smaller plant that appears healthy in all other respects. The plants may have darker green leaves that, in some cases, are thicker and more succulent. Visual symptoms, such as leaf burn, necrosis, and defoliation occur in some species, particularly woody crops. To prevent salts in the soil water from reducing water availability to the plant, the plant cells must adjust osmotically; that is, they must either accumulate salts or synthesize organic compounds such as sugars and organic acids. These processes use energy that could otherwise be used for crop growth (Maas and Grattan, 1998).

The heightened sodicity and salinity of water discharged from CBM extraction wells to soils may require mitigation and management to return the soil system to past land use capabilities. Francois (1981) reported that an efficient, economically feasible soil reclamation strategy was necessary to reverse deteriorating soil conditions associated with long-term irrigation with water of relatively high salinity and sodicity concentration.

Methods of Salinity and Sodicity Management

Approaches to manage the effects of salts in the soil include gypsum amendment application, leaching, and plant species bioremediation or phytoextraction (Helalia et al., 1990). Amending soils with gypsum is the most commonly implemented management strategy currently being employed. There is ample evidence that gypsum reduces the exchangeable sodium percentage (ESP) of the soil by exchanging calcium for sodium on cation exchange sites. Over a period of years, when sufficient rainfall is present and soil characteristics are appropriate, the applied chemical amendment will solubilize (Dollhopf, 2000). However, when amendments that decrease ESP are used, there is an increase in the total dissolved solids (TDS) or salinity of the soil solution. This results in an increase in the need for excess irrigation or rainfall to perpetuate increased leaching of the salts below the root zone (Oster and Rhodes, 1975).

Leaching, or the application of excessive water above the needs of the plant, has been linked to EC reductions within the soil profile. Numerous studies have demonstrated that salt concentrations of drainage waters and accumulation of salts in the soil decreases as leaching fraction increases (Oster and Rhoades, 1975; Jury and Pratt, 1980; Bauder and Brock, 1992). However, a soil that is both saline and sodic may drain freely at first, but after some of the salt has been removed, further leaching of the salt becomes difficult or impossible. Therefore, the results of salt leaching cannot be predicted with certainty (U.S. Department of Agriculture, 1992).

Gypsum amendment, salt leaching, and phytoremediation (salt removal by plants) for salt reclamation were compared by Helalia et al. (1990). Phytoremediation using Amshot grass (*Echinochloa stagninium)* resulted in a greater reduction in the ESP of the surface layer as compared to pond leaching and gypsum. Results indicated that Amshot grass was able to extract salts from the soil profile suggesting the potential use of plants in the remediation of saline-sodic soil conditions. Reduction in exchangeable sodium was accompanied by a decrease of 42-45% in SAR within the upper 45 cm of soil. In addition, Amshot grass significantly reduced the salinity of the soil, compared to either ponding or gypsum, and produced higher fresh yield than clover cultivated in such soils (Helalia et al., 1990)

Phytoremediation Strategy

Phytoremediation is the use of plants to remove contaminants from soil and water and is often referred to as bioremediation, botanical-bioremediation, and green remediation (Miller, 1996). Phytoremediation includes rhizofiltration (absorption, concentration, and precipitation of heavy metals by plant roots), phytoextraction (extraction and accumulation of contaminants in harvestable plant tissue such as roots and shoots), and phytostabilization (absorption and precipitation of contaminants by plants) (Miller, 1996). Phytoextraction, usually used in metal sequestration, is the process whereby plant species mitigate negative effects from salts found in the soil profile or harvest salts from shallow groundwater. Hoffman (1986), an agricultural scientist, hypothesized that beneficial effects of plants in reclamation are not well understood but appear to be related to the physical action of the plant roots and the ability of crops to uptake salts.

Although phytoremediation strategies are commonly implemented after salts have concentrated in the soil, it is conceivable that salts could be directly mined from shallow groundwater during extensive water dispersal resulting from irrigation with CBM water.

The Use of Halophytes in Phytoremediation

Halophytes are salt tolerant plants. Boyko (1966) suggested that halophytes may be used to desalinate soil and water (Boyko, 1966). Boyko did not distinguish between sodium and other salts, however, plants that accumulate sodium salts could be used to remove sodium from the substrates they grow in (Helalia et al., 1990).

Halophytes can be either ion accumulators or ion excretors. Both function to phytoremediate excess salinity and sodicity present within the soil profile by accumulating salts in aboveground plant tissue or excreting salts onto the leaf surface. These salts are then removed through plant harvest or browsing by animals (Rush and Epstein, 1981). Halophytes can further be classified according to the type of mineral ions (salts) the plants are able to accumulate or excrete. Chlorine halophytes exhibit an internal ion composition dominated by Na^{+1} and Cl^{-1} ions. This is in contrast to alkali halophytes, which exhibit relatively higher concentration of K^{+1}, Mg^{+2}, and Ca^{+2} (Redman and Fedec, 1987).

Even as early as 1964, ion-accumulating species of plants were being used in saline site remediation. The leaves of Suaeda vera Forsk (*Suaeda fruticosa*) grown in saline-sodic soils contained 9.06 % salt on a fresh weight basis, and stems had a salt content of 4.29 % fresh weight. On average, a single plant is able to produce 935.0 g of fresh leaf tissue and 232.0 g of fresh stem tissue (Chaudhri et al., 1964). Based on these values, a single plant could accumulate 94.65 g of salt in the aboveground biomass. Considering that a single *S. fruticosa* covers an area of 0.36 square meters, approximately 2352.8 kg of salt could be removed from one hectare of soil within a period of one year. The investigator suggested that three times as much salt could be "harvested" if the plants were being more effectively cultivated (Chaudhri et al., 1964; Rengasamy and Sumner, 1998).