The Role of Plants in Bioremediation of Coal Bed Methane Product Water

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ABSTRACT

Coal bed methane (CBM) exploration and development has increased substantially over the past ten years, with the Powder River Basin in Wyoming and Montana emerging as one of the most active new locations for exploration. Today, almost 6% of total United States production of methane occurs in this area. Methane extraction co-produces an excess of water, which can be saline-sodic. The water that is co-produced is spread onto the land or impounded in ephemeral draws. This water has the potential to elevate the saline-sodic conditions of the soil, causing decreases in land productivity.

It is hypothesized that specific species of plants can function to uptake excess salts and remediate the saline-sodic conditions associated with CBM discharge water. Early research has pointed towards possible successes in this approach. Studies in Europe, Egypt, and the United States suggest that species called halophytes, defined as "salt tolerant accumulators," have successfully achieved excess salt uptake by their roots. These species can accumulate high concentrations of sodium and other salts in their above ground tissue and, in some cases, can excrete these salts through nodes or on leaf surfaces.

Synthesis of this research suggests that phytoremediation, or remediation by plants, functions best in rotation or in combination with similar functioning plant species. Field crops, particularly barley, wheat, sorghum, cotton, and sugar beets, have been used extensively in phytoremediation of saline-sodic sites worldwide.

CBM Background

Exploration, development, and production within the CBM 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 6% of U.S. total production (Rice et al., 2001).

Product Water Volume

As a part of CBM extraction , water is also brought to the land surface. Water extraction reduces hydrostatic pressure within the coal seam, thereby stimulating desorption of methane from coal particle surfaces. During CBM production, this water is continuously pumped into containment areas, discharged to nearby stream channels, or spread onto the land and into ephemeral stream depressions. As with gas production, water production has increased significantly as CBM development has advanced. The possibility of millions of gallons of water discharged per day has become a realistic statistic in recent literature (Rice et al., 2001).

Product Water Sodicity

Chemistry of CBM product water has been the focus of much research lately. Samples with relatively high concentrations of salinity and sodicity have been recorded from wells in the Powder River Basin, as well as the adjacent Tongue River Drainage (Rice et al., 2001). Sodium adsorption ratios (SAR) and electrical conductivity (EC) levels of some CBM product water have exceeded published standards for all land uses, with the exception of domestic and livestock uses. According to the USDA and the University of California Extension Service, most discharge water is sodic (USDA, 1979). In sodic soil systems, exchangeable sodium ions are so concentrated in the soil that they may adversely affect plant growth and often have an adverse effect on soil physical properties. An SAR of 10 or greater indicates a sodic soil (USDA, 1979).

Sodicity frequently affects soil physical characteristics. The chemical characteristics and hydration status of sodium provide it with properties of a dispersing agent. Excessive sodium, when not balanced with divalent cations, causes soil aggregate structure to disintegrate or disperse. An excess of sodium on the cation exchange sites of fine-textured soils forms a condition in which irrigation water entering the soil is attracted to small pores with a great amount of force, resulting in soil swelling, particle slaking from aggregates, and dispersion, thus precluding drainage. Upon drying, dispersed soil particles undergo a reorientation, resulting in lost soil structure, lower hydraulic conductivity, and surface crusting that can break plant stems, inhibit germination and emergence, and slow infiltration (Dollhopf, 2000).

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. This is the period when CBM discharge is likely to contact surface soils (Rengasamy and Sumner, 1998).

Product Water Salinity

CBM discharge water is characterized by modest saline levels and may pose an environmental constraint on plant production in affected soils. A saline soil is one containing sufficient salts to interfere with growth of most plant species and is defined as having a saturated extract EC greater than 4 mmhos/cm (ds/m) (USDA, 1979), at which the growth rate of some plant species may decrease. Salinity has the potential to have significant impacts on plant communities, plant community sustainability, and livestock and wild life forage capabilities. In the absence of a well drained soil matrix or adequate irrigation or precipitation, salt leaching may not occur and over time the soil may become saline.

According to Maas (1993), the most common effect of salinity is a general stunting of growth. They (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. This loss in plant productivity is not solely a phytotoxic response, but is also related to osmotic stress (Bauder et al., 1992).

Increased salt concentration in irrigation water can directly affect pH of the soil environment. Research by Bohn et al. (1985) asserts that increasing salt concentrations usually decrease pH by displacement of hydrogen and aluminum with cations in solution, allowing the aluminum ion to hydrolyze and further lower pH. The lowering of pH can lead to phytotoxic soil characteristics. By decreasing solubility of trace metals in the soil and immobilizing nutrients, plant species production may be limited.

Saline-sodic conditions potentially created by CBM discharge water will require mitigation in order to return the soil system to past land use capabilities. The notion of reclaiming salt affected soils was conceived of long before the science of CBM reclamation was considered. In 1981 Francois (1981) claimed 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 total dissolved solid (TDS) concentration and SAR.

The Role of Bioremediation

Numerous suggestions have been advanced to remediate the effects of salts in the soil. At the core of these saline-sodic remediation methods are: 1) amending affected soils with gypsum treatments, a reclamation technique that has been adopted by soil scientists throughout the world, 2) leaching, a method to dilute and transport salts by water inundation, and 3) plant community bioremediation, a function of plant species ability to mitigate salts in soil solution either by plant uptake or chemical alteration of the soil. Present research points to the third remediation method as the most environmentally sustainable method in dealing with the saline-sodic condition. 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, the addition of organic matter, the increase in dissolution of $CaCO_3$, and crop uptake of salts.

In a publication entitled "Bioreclamation of saline-sodic soil by Amshot grass in Northern Egypt," Helalia et al. (1992) reported the effects of Amshot grass (*Echinochloa stagnina*) compared to ponding and gypsum on reducing alkalinity and salinity of highly saline-sodic soil in Northern Egypt. Their results indicated that Amshot grass reduced the exchangeable sodium percent (ESP) of the surface layer more than did either ponding or gypsum treatment. Reduction in exchangeable sodium was accompanied by a 42-45% decrease in SAR within the upper 45 cm (18 inches) of soil. In addition, Amshot grass significantly reduced soil salinity compared to either ponding or gypsum and produced higher fresh yield than clover (*Melilotus officinalis*) cultivated in such soils. Additional studies have led to similar findings. Thus, the role of plants in saline-sodic remediation has become accepted by many of the environmental sciences, and federal funding is increasing in these areas of research and development.

University of California-Riverside professor J. D. Oster (2001) identified four criteria needed to achieve sustainable soil quality and plant production: 1) salt tolerant plant species, 2) cropping strategies that maintain a year round cover to minimize the adverse impacts of rainfall, 3) periodic application of nonsaline-nonsodic irrigation waters, and 4) routine monitoring of soil solution chemistry and irrigation water quality. With this in mind, it can further be hypothesize that selected plant community types, functioning as salt tolerant halophytes, ion accumulators/excretors, and species that tend to promote soil permeability, combined with accurate water management strategies, can reduce some of the negative effects of elevated CBM product water salinity and sodicity.

The term phytoremediation applies to the above hypothesis. Phytoremediation, often referred to as bioremediation, botanical-bioremediation, or green remediation, is the use of plants to make contaminants non-toxic. 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).

Halophytes

The term halophyte, referring to salt tolerant plants (in Helalia et al., 1990), has been used in science for many years. Boyko (1966) was one of the first to suggest that halophytic plants could be used to desalinate soil and water. The hypothesis set forth by Boyko does not distinguish between sodium and other salts. However, it stands to reason that plants that are able to accumulate sodium salts could be used successfully to remove sodium from the substrates they are grown in (Helalia et al., 1990).

Ion Accumulators

Halophytes have evolved different mechanisms to deal with excess sodium and other salts in their environments. Some vascular halophytes accumulate high levels of sodium and other salts in their above ground tissue while others do not (Gorham et al., 1987). Two classes of functioning halophytes are ion accumulators and ion excretors. Both function to phytoremediate excess salinity and sodicity present within the soil profile. Ion accumulators, also called hyper-accumulators, have evolved to take up high concentrations of ions as an adaptation mechanism to saline environments. The accumulation of salts is thought to reduce the requirements for increased wall extensibility, leaf thickness, and water permeability that might otherwise be required to maintain positive growth and turgor at low soil water potentials (Rush and Epstein, 1981).

Holmes (2001) has conducted extensive laboratory and field investigations of the ecology of plants in extreme environments in an effort to select plants that are suitable for phytoremediation in saline sites. She has successfully used native halophyte plants to reclaim salt contaminated soils in Ohio, Oklahoma, and Texas. A joint project with Exxon biologists at a site near Houston, TX has met with great success. Holmes (2001) reports that content of sodium in the soil was decreased by 65% two years after planting with salt accumulating plants.

As early as 1964, ion-accumulating species were being used in saline site remediation. Chaudhri et al. (1964) reported on investigations examining the ability of Suaeda vera Forsk (*Suaeda fruticosa*) to accumulate sodium and other salts. The leaves of this plant were found to contain 9.06% salt on a fresh weight basis. A salt content of 4.29% fresh weight was measured in the stems. On average, a single plant was able to produce 935 g of fresh leaf tissue and 232 g of fresh stem tissue. Based on these values, it was determined that a single plant could accumulate 95 g of salt in its above ground biomass. Considering that a single *S. fruticosa* plant covers an area of 0.36 square meters, approximately 2,353 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; Rengasamay and Sumner, 1998).

Two ion accumulators that have been repeatedly referenced in the scientific literature are rice (*Oryza sitiva*) and sunflower (*Helianthus annuus*). Rice cultivation has been recognized to improve saline soils. According to Iwasaki (1987), the salt content of the 5 to 10 cm soil depth was reduced to less than one-fifth the original salt content after a single year of rice cultivation. While improvement of the soil may have been caused primarily by the leaching effect of rice cultivation, the rice plant does contribute to soil improvement by accumulating salts in its shoots (George, 1967).

Bhatt and Indirakutty (1973) reported that 83 kg of sodium could be removed from one hectare of land via accumulation by sunflower plants. The investigators concluded that sunflower plants gradually reduce soil salinity with the harvest of the edible sunflower oil.

EC can also be mitigated by ion accumulating species. Sharp-leaved rush (*J. acutus*) and Samaar morr rush (*J. rigidus*), which have traditionally been used for weaving floor mats, are also considered as an alternative pulp material for paper production. Researchers attempting to reclaim poorly drained soils in Egypt recognized that these two species are cumulative halophytes (ion accumulators) which concentrate salts in the upper parts of their shoots. Horizontal rhizomes of these plants were transferred to a poorly drained, saline soil and allowed to grow. The amount of total soluble solids (TSS) in the soil was measured before planting and after harvest. On average, a single growth cycle of *J. acutus* reduced the TSS of the soil from 1.03% to 0.08% while a decrease from 1.07% to 0.65% was measured in the soil containing *J. rigidus*. For *J. rigidus*, this translated to a decrease in EC from 33 to 20 mmhos/cm (ds/m) in soil having a 50% saturation percentage (Zahran et al., 1982).

Ion Excretors

Excretive halophytes make up the second component of this functioning class of phytoremediating plants. Excretive halophytes possess glandular cells or vesiculated trichomes (leaf hairs), which are able to excrete sodium and other salts from their leaf tissue. Tamarix species (salt cedar) and Atriplex species (saltbush) are examples of plants that possess salt excreting glanular cells and trichomes, respectively (Kelly et al, 1982).

Atriplex is from the family Chenopodiaceae, which contains about 20% of all halophyte species (Glenn et al., 2001) and is well known for having very high internal concentrations of sodium ions. Excretive halophytes commonly found in CBM production areas of Montana and Wyoming includes Chenopodium (goosefoot), Kochia (summer cypress), Salicornia (saltwort), Salsola (Russian thistle), and Suaeda (sea blite) (Dorn, 1984). The potential use of Atriplex as a forage or animal feed makes its use for soil salt and sodium removal attractive. A hectare (2.47 acres) of Atriplex has the potential to produce 16,000 kg (35,274 lbs) of dry forage matter per year (Goodin and Mckell, 1970).

Halophytes can further be classified according to the type of mineral ions (salts) they are able to accumulate or excrete. Chlorine halophytes exhibit an internal ion composition dominated by Na and Cl ions. This is in contrast to alkali halophytes, which exibit relatively high concentrations of K^+, Mg^{2+}, and Ca^{2+} (Redman and Fedec, 1987).

Rooting Action

While halophytic species can effectively phytoremediate a saline-sodic system by interacting with salts in the soil-water environment and reducing them through absorption, the physical characteristics of rooting can also increase soil permeability and result in leaching of salts beyond the root zone. Root decomposition frees channels for water movement, thereby increasing hydraulic conductivity of the soil. Yadav (1975) reported that the extensive root system of paddy rice loosened the soil, making it more permeable to leaching of salts.

Other studies have reported that sorghum (*Sorghum spp.*) increases soil pore sizes and water infiltration and leads to greater saturated hydraulic conductivity (Skidmore et al., 1986). Robbins (1986) reported that a sorghum-sudan grass (*Sorghum-Sudanese spp.*) hybrid crop produced high soil atmospheric CO_2 concentrations and greater Na leaching efficiencies than several other crops and amendment treatments

Assessments of this research, especially the work by Robbins, suggest that these plant functions work to phytoremediate best when used in rotation or combination with like plant species. As early as 1972, studies suggested that alternating or interseeding plants, in this case barley (*Hordium spp.*) or rice, would accelerate reclamation and the bioremediation process (Saraswat et al., 1972).

Cropping Options

Field crops, particularly barley, wheat (*Triticum spp.*), sorghum (*Sorghum spp.*), cotton (*Gossypium spp.*), and sugarbeet, have been used extensively in bioremediation of saline-sodic sites. By utilizing more water on these crops than actually needed, salts and sodium can be leached beyond the roots and the soil can be prepared for more sensitive crops (Oster, 2001). Yadav (1975) and later Bauder et al. (1992) and Bauder and Brock (1992) present a similar diagnosis to that given by Oster. They suggest that cropping can play a significant role in reclamation of saline and alkali soils and managed crop systems are essential for achieving continued improvement of such soils.

Bauder and Brock (1992) concluded that uncropped conditions, which maintain the soil at a relatively high water content and minimize repeated drying and rewetting of the soil, and crops such as sorghum-sudan grass, which cause rapid drying of the soil and create conditions conducive to leaching salts, may be the best combination of conditions to gain maximum efficiency of amendments applied to reclaim saline or sodic soil. They further suggest that a primary halophyte species or combination of like species can help to set the stage for complete restoration by amendments. In the Powder River Basin, this may be the best appraoch to reclamation after CBM production has ended.

In conclusion, product water quality associated with CBM extraction has the potential to significantly impacts soil chemistry, plant community production, and land class capabilities in discharge areas and affected regions. In general, it is hypothesized that plant species, including halophytes, can function to phytoremediate saline-sodic conditions through the intrinsic characteristics possessed by the specific species or community. In combination with scientific irrigation strategies, interseeding, crop rotation, and post discharge amendments, such as with gypsum, pre-development land capabilities can be achieved in these affected systems.

Species List

Common Name	Scientific Name	Function
Amshot Grass	Echinochloa stagnina	ion accumulator
Suada vera Forsk	Suaeda fruiticosa	ion accumulator
Rice	Oryza sitiva	ion accumulator
Sunflower	Helianthus annuus	ion accumulator
Sharp-leaved rush	Juncus acutus	ion accumulator
Samaar morr	Juncus rigidus	ion accumulator
Salt Cedar	Tamarix L.	ion excretor
Goosefoot	Chenopodium spp.	ion excretor
Summer Cypress	Kochia spp.	ion excretor
Salt Wort	Salicornia spp.	ion excretor
Russian Thistle	Salsola spp.	ion excretor
Seablite	Suaeda spp.	ion excretor
Sorghum-sudan grass	Sorghum-sudanese	soil pore size enhancer
Barley	Hordium spp.	limited ion accumalator
Wheat	Triticum spp.	limited ion accumulator
Cotton	Gossypium spp.	limited ion accumulator
Sugarbeet	Heterodera spp.	limited ion accumulator

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