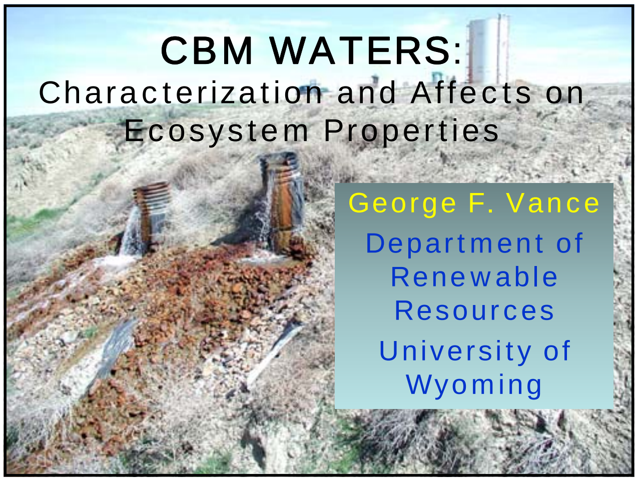


Introduction

- **Water Quality**
  - pH, EC, SAR, Alkalinity, Trace Elements
    - pH determines acid-base nature of the solution
    - EC is a measure of salt content (1.0 dS/m = 0.87 ton of salt/acre foot of water (7758 barrels)
    - SAR is the ratio of Na to Ca + Mg
      SAR ($mmol^{1/2}$ $L^{-1/2}$) = $[Na^+]/ [Ca^{2+} + Mg^{2+}]^{1/2}$
    - Alkalinity is a measure of HCO_3^- and CO_3^{2-}
    - Trace Elements (Al, As, B, Cl, Se, etc.)
  - Agricultural water use (Irrigation Standards)
    - EC < 0.75 dS/m
    - SAR < 10
    - Residual Sodium Carbonate (RSC) <1.25
      RSC = $[HCO_3^-$ and $CO_3^{2-}] – [Ca^{2+} + Mg^{2+}]$

Introduction

- **Soil Properties**
  - Texture and Structure
  - Mineralogy and Organic Matter
    - Clay mineral type and OM properties
  - EC vs ESP

	EC (dS/m)	ESP
Nonsaline/nonsodic	< 4	< 5
Nonsaline/sodic	< 4	> 15
Saline/nonsodic	> 4	< 15
Saline/sodic	> 4	> 15

  - Impacts to soil physical and chemical properties
    - Infiltration and Permeability
      Function of soil texture and structure
    - Physical disruption - aggregate slaking and clay particle dispersion
    - Crusting

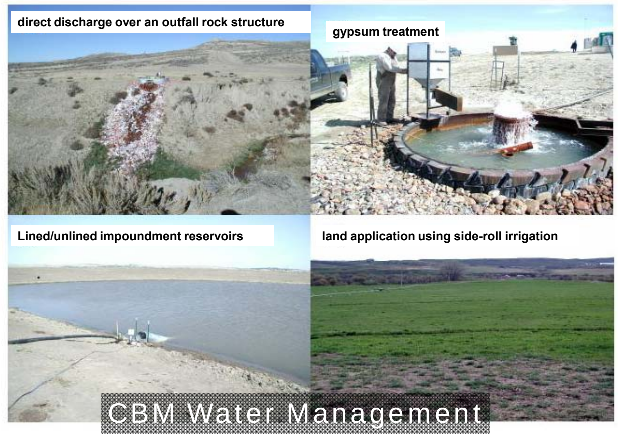
Introduction

- **Plant Responses**
  - Salinity (salts)
    - Osmotic effects (water relations)
    - Specific ion effects (nutrient balance)
  - Sodicity (Na)
    - Non-essential
    - Na toxicity
  - Plant germination, emergence, root development, growth, yield
  - Plant specific irrigation water use
    - Water logging vs water deficiencies
    - Infiltration
    - Hydraulic conductivity
    - Aeration
    - Nutrient availability

CBM Water Quality

- **High concentrations of soluble salts**
  - **Electrical conductivities (EC)—0.4 to 4.5 dS m^{-1}**
  - **Total dissolved solids (TDS)—300 to 2,800 mg L^{-1}**
- **High concentrations of Na^{+}**
  - **SAR—5 to 70 $mmol^{1/2}$ $L^{-1/2}$**
- **High bicarbonate concentrations**
  - **Up to 3200 mg L^{-1}**

(Rice, Ellis and Bullock, 2000; Wheaton and Olson, 2001; Phelps and Bauder, 2003; Ganjegunte et al., 2005, 2008)



CBM Waters

Soil and Vegetation Considerations

Na^{+} and soluble salt accumulation in soils, particularly on fine textured soils.

Negative impacts on infiltration rates and soil water flows

Alteration in relative species composition and dominance of vegetation community

- differential tolerances of individual species and life-forms to altered soil environmental conditions

Short-term CBM Water Irrigation Study

18 research blocks – 4 plots each.

Soil pits – 9 total

Soil series

- –Forkwood – silty clay loam
- –Ulm – silty clay loam
- –Kishona – loam

Irrigation with coalbed natural gas co-produced water. Johnston, Vance and Ganjegunte. 2008. Agricultural Water Management 95:1243-1252.

Soil-Water Treatment Study

Site Characteristics
- 15 ha irrigated field near UCross, WY
- Flood irrigated for the last 10 years
- Used for grazing and hay grass
- Planted in alfalfa/grass mix in 1995

Plots monitored for
- Effects of gypsum and S on pH, EC, SAR, and SO_4^{2-} concentrations
- Used a split plot experiment
- Baseline and post treatment soil samples collected to 60 cm

Irrigation water treatments and surface amendments

- Treatments/amendment added to CBM water/soil to reduce soil impacts
- Water treatments included:
  1. No treatment
  2. Solution grade gypsum
  3. No. 2 plus S burner (SO_2 production)
- Soil amendments included:
  1. No treatment
  2. Gypsum (3.4 Mg ha^{-1})
  3. Agricultural S (1.1 Mg ha^{-1})
  4. Combination of No. 2 and 3

Irrigation water treatments and surface amendments

Water Used	Surface Applied Soil Treatment	Water Treatment Before Irrigation	Abbreviations Used
Piney Creek (PC)	none	none	PC+NT
PC	gypsum	none	PC+G
PC	sulfur	none	PC+S
PC	Gypsum & sulfur	none	PC+GS
CBM	none	none	CBM+NT
CBM	gypsum	none	CBM+G
CBM	sulfur	none	CBM+S
CBM	Gypsum & sulfur	none	CBM+GS
CBM	none	gypsum injector	CBM-G+NT
CBM	gypsum	gypsum injector	CBM-G+G
CBM	sulfur	gypsum injector	CBM-G+S
CBM	Gypsum & sulfur	gypsum injector	CBM-G+GS
CBM	none	gypsum inj. & sulfur burner	CBM-GSB+NT
CBM	gypsum	gypsum inj. & sulfur burner	CBM-GSB+G
CBM	sulfur	gypsum inj. & sulfur burner	CBM-GSB+S
CBM	Gypsum & sulfur	gypsum inj. & sulfur burner	CBM-GSB+GS

Irrigation and CBM Water Chemistry

Water Sample	pH	EC	TDS	ALK	Na^+	Ca^{2+}	Mg^{2+}	SAR
	s.u.	dS/m	mg/L	mg/L	mg/L	mg/L	mg/L	$mmol^{1/2}$ $L^{-1/2}$
Piney Creek	8.3	0.64	470	207	28.1	74.8	29.5	0.69
CBM	8.3	1.38	910	802	344	8.9	3.9	24.3

	K^+	Fe	Cl^-	F^-	HCO_3^-	CO_3^{2-}	RSC	SO_4^{2-}
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	$mmol_{(c)}$/L	mg/L
Piney Creek	5.8	100	2.5	0.19	237	7.5	<1	137
CBM	3.1	560	12.8	0.94	853	61.5	15.3	<1.0

Saturated Paste Extract EC (dS/m)

Water Treatment	Soil Horizon	Pre Irrigation	Post Irrigation (2004) Soil Treatment NT	G	S	GS
PC	A	0.84 - 0.89	0.94	1.5	1.5	2.1
	Bt_1	0.61 - 0.62	0.81	1.4	1.0	1.6
	Bt_2	0.55 - 0.58	0.76	2.1	3.0	2.1
CBM	A	0.83 - 1.2	1.5	2.1	2.4	2.8
	Bt_1	0.54 - 0.76	0.80	1.9	1.2	1.9
	Bt_2	0.51 - 0.59	0.73	2.0	1.1	2.0
CBM-G	A	0.73 - 0.87	1.8	2.5	2.4	2.5
	Bt_1	0.53 - 0.63	1.3	1.8	1.6	1.9
	Bt_2	0.50 - 0.55	1.0	2.2	1.7	2.2
CBM-GSB	A	0.86 - 1.0	2.0	3.9	3.1	3.7
	Bt_1	0.43 - 0.60	1.8	3.3	2.1	2.6
	Bt_2	0.47 - 0.53	1.7	2.6	2.1	2.5

Saturated Paste Extract SAR ($mmol^{1/2}\ L^{-1/2}$)

Water Treatment	Soil Horizon	Pre Irrigation	Post Irrigation (2004) Soil Treatment NT	G	S	GS
PC	A	0.30 - 0.37	0.77	0.54	0.56	0.47
	Bt_1	0.51 - 0.65	0.73	0.52	0.63	0.60
	Bt_2	0.43 - 0.62	0.85	0.62	0.67	0.56
CBM	A	0.25 - 0.45	7.7	5.6	6.1	4.5
	Bt_1	0.48 - 0.63	2.3	2.0	2.7	2.4
	Bt_2	0.58 - 0.64	1.3	0.94	1.1	0.92
CBM-G	A	0.28 - 0.38	7.5	5.6	5.7	5.0
	Bt_1	0.49 - 0.60	2.9	3.2	2.7	2.8
	Bt_2	0.63 - 0.66	1.0	1.0	0.86	1.0
CBM-GSB	A	0.32 - 0.39	5.5	3.7	4.4	3.9
	Bt_1	0.42 - 0.58	2.7	2.7	3.7	3.4
	Bt_2	0.55 - 0.75	1.1	1.1	1.2	1.2

2006 Post Irrigation Infiltration Rate (IR) (mm/hr)

Water Treatment	Soil Amendment NT	G	S	GS
PC	25.3[a]	27.1[a]	25.0	24.6[ab]
CBM	12.2[b]	13.5[b]	17.7	17.7[b]
CBM-G	13.2[ab]	22.1[ab]	21.5	23.8[ab]
CBM-GSB	18.2[Bab]	25.8[ABab]	27.0[AB]	33.5[Aa]

Capital letters indicate a significant difference between means of amendments ($P \leq 0.05$).
Lower case letters indicate a significant difference between means of water treatments ($P \leq 0.05$).

RESULTS
Soil-Water CBM Study

EC and SAR increased with all treatments in the top two soil depths

Water treatments resulted in:

- CBM water increasing EC and SAR in surface soil
- CBM-G water had no effect on SAR in the A horizon compared to CBM water
- CBM-GSB water was the most effective treatment for SAR
- Higher soluble Ca^{2+} when HCO_3^- was removed with SB
- CBM water IR lower than PC control

RESULTS
Soil-Water CBM Study

Surface amendments resulted in:

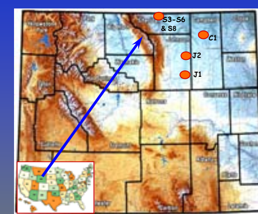
- GS lowering A horizon SAR compared to G or S amendments
- SAR of all soil amendments lower than CBM and CBM-G water treatments
- No differences in Bt1 and Bt2 SAR with surface amendments
- GS amendments + GSB water treatment effective in maintaining low surface SAR
- CBM-GSB water treatment with GS soil amendment highest IR

Multiple Site CBM Study

Soil Studies

6 sites - sampled 2003 & 2004

- **6 depth intervals (0 - 120 cm)**
  - **pH**
  - **EC**
  - **SAR**
  - **ESP**
  - **texture**
  - **bulk density**
  - **infiltration rates**
  - **Darcy flux**



Vegetation Studies

5 sites with native plant communities (3 original and 2 new sites) - sampled 2004 and 2005

- **production, cover, frequency, species richness, evenness, AM fungi infectivity on dominant grass species**

Land application with saline-sodic coalbed natural gas water: cumulative effects on soil chemical properties. Ganjegunte, King, and Vance. 2008. J Environmental Quality 37:S128-S138

Soil and Plant Responses from Land Application of Saline–Sodic Waters: Implications of Management Vance, King, and Ganjegunte. 2008. J Environmental Quality 37:S139-S148

Study Site Characteristics

Site (CBM irrigated)	Application & Treatment Methods	Soil Amendments	Vegetation Type/ dominant species
1 (3yr)	Center Pivot water not treated	Surface application Gypsum/Sulfur	Seeded perennial grasses/western wheatgrass
2 (1 yr)	Center Pivot Zeolite	None	Seeded 2003/ germinating oats
3 (3 yr)	Side Roll Sulfur Burner	Surface application Gypsum/Sulfur	Native grassland /needle and thread grass
4 (2 yr)	Center Pivot Sulfur Burner	Surface application Gypsum/Sulfur	Hayfield/Alfalfa & intermediate wheatgrass
5 (2 yr)	Side Roll Sulfur Burner	Surface application Gypsum/Sulfur	Hayfield/Smooth Brome & alfalfa
6 (3 yr)	Side Roll Sulfur Burner	Surface application Gypsum/Sulfur	Native grassland/ western wheatgrass

Study Site Characteristics

Water Quality

2003 pH 7.8 - 8.9
EC 1.4 - 4.0 dS/m
SAR 15 - 38 $mmol^{1/2}\ L^{-1/2}$

2004 pH 6.9 - 9.1
EC 1.6 - 4.9 dS/m
SAR 18 - 57 $mmol^{1/2}\ L^{-1/2}$

Recommended for irrigation use
EC 0.75 dS/m
SAR <10 $mmol^{1/2}\ L^{-1/2}$

Results – CBM Irrigation

SOIL EC

- 14 of 36 irrigated sample depths were saline (>4 dS m^{-1}) vs 3 of 36 control site depths
- EC greater (p=0.05) on irrigated vs control sites:
  - 0-120 cm on clay soil irrigated sites
  - 0-60 cm on course soil irrigated sites
  - 0-30 cm on site with 1+ seasons of CBM water application

Results – CBM Irrigation

SOIL SAR

- 7 of 36 irrigated sample depths were sodic (>13 $mmol^{1/2}$ $L^{-1/2}$) vs 0 of 36 control site depths
- SAR greater (p=0.05) on irrigated vs control sites:
  - 0-120 cm on SB treated, clay dominated irrigated sites
  - 0-60 cm on non-SB treated clay dominated irrigated sites

Results – CBM Irrigation

SOIL ESP

- 23 of 36 irrigated sample depths were sodic (>15%) vs 1 of 36 control site depths
- ESP greater (p=0.05) on irrigated vs control sites:
  - 32 of 36 irrigated sample depths
  - all treated areas to 30 cm

Results – CBM Irrigation

Infiltration Rate (cm/hr)

Site	May Irrigated	May Control	p value	October Irrigated*	October Control	p value
1	0.0	9.2	<0.01	0.0	10.7	<0.01
2	0.3	4.6	<0.01	0.2	5.3	<0.01
3	6.5	8.1	0.11	7.1	9.4	0.07
4	2.2	7.2	0.12	3.1	11.9	0.02
5	13.8	21.5	0.06	9.0	14.4	0.07
6	6.5	7.2	0.43	0.4	11.9	<0.01

* All late season irrigated sites had infiltration rates slower than control sites.

Results – CBM Irrigation

Flux Rates

- Site 1 (0-120 cm) & site 4 (0-60 cm) had significantly slower flux rates
- Other irrigated sites had slower rates at most depths – no significant trends
- 2003 vs 2004 – Flux rates were significantly slower at most irrigated sites & depths

Soil Impacts from CBM Water

Irrigation with CBM waters resulted in:

- Salinity/sodicity exceeded irrigation H_2O limit
- Increasing soil (SPE)
  - EC to 120 cm on heavy clay soils (>2+ yrs)
  - EC to 60 cm on sandy clay loam texture
  - EC & SAR to 30 cm on site irrigated 1.5 yrs
  - SAR to at least 60 cm (up to 120 cm) on heavy clay soils
  - Variable SAR (0-120) on sandy clay loam soil textures.
- Decreasing soil
  - surface water infiltration rates
  - Darcy flux rates to depths of 120 cm

Vegetation Impacts from CBM Water

Irrigation with CBM waters resulted in:

- Reduced community diversity & evenness
- Increased perennial grass production, total vegetation biomass & aerial cover of salt/Na tolerant plants
- Other species had decreased biomass production and aerial cover
- Had no affect on plant species richness
- Variable impacts to native plant species

Irrigation Water

- Acceptable levels of salinity and sodicity of irrigation water influenced by:
  - climate (particularly rainfall)
  - soil type
  - crop and plant species
  - management practices
- Rainfall can increase Na hazard
  - flushes salts elevating bound soil Na
  - **increase the likelihood that sodium-induced dispersion**

CBM Water Management Strategies/Goals

- Maintain soil moisture at or near field capacity to maximize unsaturated (vs. saturated) flow
- Leach soluble salts and Na^+ through soil profile and out of plant rooting zone
- Add soil amendments to supply Ca^{2+} and Mg^{2+} ions to replace Na^+ on soil exchange sites

Tier 2 Risks

- Unmanaged versus managed irrigation
- Does not protect agronomic plants
  - ✓ Water quality versus quantity
  - ✓ Plant growth requirements
- Does not consider importance of soil properties
  - ✓ Clays (shrink-swell smectites)
  - ✓ Organic matter
- Sampling protocol

Tier 2 Risks

- Concerns raised by experts in Soil Science and Irrigation Technologies
  - ✓ Dr. D.L. Suarez - ***Director,*** USDA-ARS Soil Salinity Laboratory
  - ✓ Dr. S.R. Grattan - ***Plant-Water Relations Specialist*** (co-author of Hanson et al. 1999)
  - ✓ Dr. J.D. Oster - ***Emeritus Specialist***, Department of Environmental Sciences, University of California and ***Co-Editor in Chief*** of Agricultural Water Management