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Selective-placement burial of drilling fluids: Effects on soil properties, buffalograss and fourwing salt-bush after 4 years

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Abstract

A field study was established in 1986 to evaluate selective-placement burial as an alternative technique for on-site disposal of drilling fluids in arid and semiarid areas. Soluble salt and heavy metal migration in the soil, and establishment, yield and chemical composition of fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) and buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) were determined 44 months after simulated reserve pits were constructed to provide burial depths of 30, 90 (with and without a 30-cm thick, coarse limestone capillary barrier), and 150 cm, with sequential replacement of stockpiled subsoil and topsoil. Soluble salt concentrations increased most significantly in the 30-cm zone immediately above buried drilling fluids, regardless of treatment. Upward salt movement was greatest in the 90- and 150-cm treatments, with significant increases in Electrical Conductivity (EC) and Exchangeable Sodium Percentage (ESP) values observed as much as 60 and 30 cm above buried drilling fluid, respectively. Capillary barriers reduced the extent of upward salt migration, but had little effect in soil zones immediately overlying the drilling fluid. There was no evidence of upward migration of Ba, Cr, Cu, Ni, or Zn from buried drilling fluids into overlying soil, but concentrations of Cu and Zn were greater in saltbush stems grown on plots with buried drilling fluids on 1 site. Fourwing saltbush survival averaged 92 to 100% and was not affected by depth of drilling fluid burial. Significant reductions in saltbush canopy cover and yield on the 30-cm burial treatment were observed on 1 study site. Elevated Na concentrations in aboveground tissue of both species in the 30-cm burial treatment on 1 site did not adversely affect survival or plant growth. Differences between study sites in the extent of upward salt movement in the soil and in plant response were attributed to differences in soil clay type and content.

Key words: salinity, sodium, hazardous waste, heavy metals, *Atriplex canescenes, Buchloe dactyloides*

Onsite, surface disposal of drilling fluids used in petroleum and natural gas exploration is a common practice in arid and semiarid regions of the southwestern United States, even though severe and permanent soil contamination occurs (McFarland et al. 1987). Selective-placement burial, a technique developed for coal mine reclamation, presents an alternative to surface disposal in which drilling fluids are worked, stored, dried, and eventually buried at a predetermined depth below the soil surface. In this process, soil contamination is minimized, the waste volume is reduced, and the potential for revegetation is enhanced.

Field research was initiated in autumn 1985 to evaluate the effects of selective-placement burial of drilling fluids on soil chemical properties and on establishment, growth, and chemical composition of 2 species used for revegetation. Results reported after 20 months showed that soluble salts had migrated upward 15 to 30 cm into overlying soil and capillary barriers of coarse limestone were only partially effective in reducing salt movement (McFarland et al. 1992a). There was no evidence of upward migration of heavy metals (Ba, Cr, Cu, Ni, Zn) from the buried drilling fluids. Survival and growth of fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) and buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) were not affected by depth of drilling fluid burial 17 months after planting, although significant increases in Na and K concentrations in both species at 1 location indicated plant uptake of drilling fluid constituents occurred where burial depth was 30 cm (McFarland et al. 1992b). A more significant finding was evidence of elevated Zn concentrations in fourwing saltbush leaf and stem tissue on plots where drilling fluid was buried 30 or 90 cm. This paper presents a comparative analysis of treatment effects on soils and plant growth based on data collected after 4 growing seasons (44 months after study initiation).

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Materials and Methods

The study was established in 1985-86 in the northwestern Edwards Plateau of Texas. Study sites were 10 km north of Big Lake in Reagan County (Weatherby site) and 34 km southwest of Mertzon ii Schleicher County (Mertz site). Reagan County is semiarid with an average annual rainfall of 430 mm and a mean annual lake evaporation of 1,800 mm (Blum 1977). The study area was on a level, upland site on a Reagan clay loam (fine-silty, mixed, thermic, Ustollic Calciorthid). The average annual rainfall in Schleicher county is 460 mm and the mean annual lake evaporation is 1,780 mm (Wiedenfeld 1980). The study site was on a flat valley floor above the overflow zone on an Angelo clay loam (fine-silty, mixed, thermic, Aridic Calciustoll).

Fifteen, 9.1- by 9.1-m simulated reserve pits separated by 9.1-m buffers were constructed at each location in August 1985 using a bulldozer. Treatments included burial of drilling fluid at 30, 90, or 150 cm, burial at 90 cm with a 30-cm capillary barrier of coarse limestone (Edwards Group) immediately above the drilling fluid, and an undisturbed control from which existing vegetation was cleared with the dozer blade. Topsoil and subsoil were removed and stockpiled separately during pit construction. Spent fluids from 2 drilling locations near each study site were transported to the sites in dump trucks in September 1985. Equal volumes of about 25 m^3 of drilling fluid were placed as a uniform 30-cm layer into each pit, allowed to dry, and then covered by sequential replacement of subsoil and topsoil in January 1986. Experimental design was a randomized complete block arranged as a split plot with 3 replications. Replications were blocked by drilling fluid source.

The study sites were fenced to exclude livestock and lagomorphs, and grass and shrub seedlings were planted in spring 1986. Each reserve pit plot was divided into two, 4.6- by 9.1-m subplots. Fourwing saltbush, a native, evergreen, halophytic shrub, and "Texoka" buffalograss, a native, perennial, warm-season shortgrass, were used to evaluate the effects of plant material on contaminant migration and as biological indicators to assay plant response to possible upward migration of contaminants or root penetration of buried waste. Forty seedlings of buffalograss were transplanted on 1-m centers on 1 subplot of each pit. Seedlings were grown in a greenhouse in an equal-volume peat moss/vermiculite/ soil mixture in 4- by 5- by 18-cm polyethylene containers and were 5 months old at transplanting. Twenty-four, 1-year-old rooted stem-cuttings of fourwing saltbush were transplanted on 1.5-m centers on the other subplot. Stem-cuttings were taken from mature plants which were established in 1982 on a highly saline reserve pit (EC = 90 dS m^{-1}, SAR = 46) near Big Lake, Texas. Stem-cuttings were rooted for about 2 weeks in a 1:1 (v:v) sand/vermiculite mixture using an intermittent misting system in a greenhouse, and then transferred to 4- by 5- by 18-cm polyethylene containers filled with an equal-volume peat moss/vermiculite/soil mixture.

Results from analyses of soil samples collected 1, 8, and 20 months after the treatments were installed were reported previously (McFarland et al. 1992a). Data presented in this paper are from similar analyses conducted on samples collected after 44 months. Sampling trenches bisecting each plot were excavated to the soil/drilling fluid (or soil/limestone) interface using a backhoe in August 1989. Samples were collected from the pit wall in 30-cm depth increments, with zones at the soil/drilling fluid and soil/air interfaces subdivided into 15-cm increments. Composited soil samples from each subplot were air-dried and ground to pass a 2-mm sieve. Saturated paste extracts were obtained using the method described in USDA Handbook 60 (U.S. Salinity Laboratory Staff 1954). Total soluble salt concentrations were estimated by measuring the electrical conductivity (EC) of saturated paste extracts. Soluble Na^+ was measured by flame emission spectroscopy. Extractable Na^+ was determined in soil extracts of neutral 1.0 *M* NH_4OAc while exchangeable Na^+ was estimated as the difference of extractable Na^+ minus water-soluble Na^+ and used to calculate the exchangeable sodium percentage (ESP) (U.S. Salinity Laboratory Staff 1954). Cation exchange capacity was determined by saturating soil samples with 1.0 *M* NaOAc, washing with ethanol, and replacing Na^+ with 1.0 *M* NH_4OAc (U.S. Salinity Laboratory Staff 1954).

Total concentrations of Ba, Cr, Cu, Ni and Zn in soil were determined after HNO_3-$HClO_4$ digestion (Nelson et al. 1984) by inductively coupled argon plasma (ICP) emission spectroscopy. Simultaneous analysis of certified, standard soil samples from the Canadian Certified Reference Materials Project was conducted to monitor accuracy.

Survival of fourwing saltbush was determined by counting the number of live plants in each subplot. Canopy cover of each species was estimated by measuring intercept along line transects (Canfield 1941) across both diagonals of each subplot. Canopy dimensions of fourwing saltbush were estimated by measuring 12 interior plants in each subplot. Canopy diameters were measured parallel with and perpendicular to the row. Shrub canopy heights were also measured. One or 2 fourwing saltbush plants from each subplot were harvested to 10 cm above ground level and oven-dried at 60° C. The biomass and canopy height and diameter data were used to develop regression equations for estimating aboveground biomass (Peterson et al. 1987). Standing crops of buffalograss were estimated by harvesting to ground line in 10, equidistantly-spaced, 0.25-m^2 quadrats in each subplot. Samples were oven-dried at 60° C to a constant weight and means calculated for each subplot.

Aboveground tissue samples were collected from 10 plants in each subplot, oven-dried at 60° C, and ground to pass a 0.15-mm sieve. Total concentrations of Ca, Mg, Na, K, Ba, Cr, Cu, Ni and Zn were determined by ICP atomic emission spectroscopy after HNO_3-$HClO_4$ digestion of composited subsamples (Nelson et al. 1984).

Soil data were treated as a split-split plot with depth of burial the main-plot effect, plant species the subplot effect, and time (20 and 44 months) the sub-subplot effect. Among treatment comparisons of upward contaminant movement in the reconstructed soil profiles were facilitated by redefining the soil/drilling fluid (or soil/limestone) interface as the zero point. Treatment comparisons for EC and ESP data were made within each increment above this reference point. The data were subjected to analyses of variance ($P<0.05$) and treatment means separated when appropriate using Fisher's least significant difference method (Gomez and Gomez 1984). Plant data were subjected to split plot analyses of variance ($P<0.05$), where depth of burial was the main plot effect and plant species was the subplot effect. Means were separated by Duncan's new multiple range test when appropriate (Gomez and Gomez 1984).

Results and Discussion

Soil Chemical Composition

Physical and chemical characteristics of the soil profiles and drilling fluids were reported previously (McFarland et al. 1992a). Average electrical conductivities of the native soil profiles (0-203 cm) at the Mertz and Weatherby sites were 1.0 (range 0.8-1.4) and 1.0 (range 0.7-1.3) dS m^{-1}, respectively, and ESP values for the 2 sites averaged 0.6 (range 0.2-2.1) and 0.8 (range 0.3-2.4), respectively. Salt contamination of the drilling wastes was the predominant concern as evidenced by EC values of 155 to 185 dS m^{-1} and ESP values of 42 to 89. Sodium and Cl^- were the dominant soluble ions, although K^+, Ca^{+2}, and Mg^{+2} concentrations were also much greater in drilling fluids than in native soils (McFarland et al. 1992a).

Rainfall at the Weatherby site during 1988 and 1989 totalled 454 and 281 mm, respectively, compared to the long-term annual average of 430 mm. Rainfall at the Mertz site totalled 514 mm in 1988 and 353 mm in 1989, compared to the long-term annual average of 460 mm. Thus, in the year preceding this evaluation rainfall was about 35 and 23% less than the long-term averages for the sites. The 20-month evaluation (McFarland et al. 1992a) occurred following a year of above-average rainfall in 1986 and average rainfall in 1987.

Salt movement into soil overlying drilling fluid was similar in subplots planted to fourwing saltbush and buffalograss, so the data were pooled for presentation. The time x depth of burial interactions were significant for EC in the 0 to 15-, 15 to 30- and 30 to 60-cm incre-

Table 1. Average soil electrical conductivities at 5 increments above drilling fluid after 20 and 44 months as influenced by depth of burial.

	Mertz site Time (months)		Weatherby site Time (months)	
Depth of burial	20	44	20	44
(cm)	--------(dS m^{-1})--------			
	-------- (Increment above drilling fluid) --------			
	-------- (0 to 15 cm) --------			
30	4.4a*	24.2bC	19.5	23.6
90	8.1	14.5B	21.1	21.0
90 + barrier	2.6	4.2A	10.6	16.4
150	9.2a	21.0bC	14.2	20.6
	--------(15 to 30 cm)--------			
30	0.5	0.9A	4.3	10.0
90	0.5a	6.8bB	5.2	37.3
90 + barrier	0.5	1.3A	3.4	8.2
150	1.4a	14.8bC	2.7	17.4
Mean			3.9a*	18.2b
	--------(30 to 60 cm)--------			
90	0.4	0.6A	0.7a	5.7bB
90 + barrier	0.5	0.5A	1.0	1.6A
150	0.8a	2.7bB	0.9a	4.2bB
	--------(60 to 75 cm)--------			
90	0.5	0.5	0.4	0.7
90 + barrier	0.5	0.4	0.5	0.8
150	0.5	0.6	0.7	0.8
	--------(75 to 90 cm)--------			
90	0.5	0.6	0.5	0.7
90 + barrier	0.5	0.8	0.5	0.6
150	0.4	0.7	0.9	0.7

* For each location, means within a depth of burial and row followed by similar lower case letters and within an increment above drilling fluid and column followed by similar upper case letters are not significantly different by LSD ($P \leq 0.05$).

Table 2. Average exchangeable sodium percentages (ESP) at 5 increments above drilling fluid after 20 and 44 months as influenced by depth of burial.

	Mertz site Time (months)		Weatherby site Time (months)	
Depth of burial	20	44	20	44
(cm)	--------(%)--------			
	--------(Increment above drilling fluid)--------			
	--------(0 to 15 cm)--------			
30	7.1	15.4	19.0	27.1
90	7.1	14.9	15.9	33.6
90 + barrier	1.9	4.9	7.3	17.9
150	6.6	19.1	14.5	34.0
Mean	5.7a*	13.6b	14.2a*	28.1b
	--------(15 to 30 cm)--------			
30	0.6	0.7A	1.6	13.2
90	0.9a	5.1bB	2.3	14.6
90 + barrier	1.1	0.9A	2.1	6.7
150	1.8a	6.9bB	2.2	13.8
Mean			2.1a	12.1b
	--------(30 to 60 cm)--------			
90	0.8	1.1	0.7	0.9
90 + barrier	1.5	1.2	1.1	0.8
150	2.0	1.9	1.8	2.4
	--------(60 to 75 cm)--------			
90	0.6	0.5	0.6	0.5
90 + barrier	1.3	1.5	0.8	1.2
150	1.8	2.1	2.0	1.8
	--------(75 to 90 cm)--------			
90	0.5	0.6	0.5	0.5
90 + barrier	0.7	0.7	0.6	0.8
150	1.2	1.0	1.9	1.2

* For each location, means within a depth of burial and row followed by similar lower case letters and within an increment above drilling fluid and column followed by similar upper case letters are not significantly different by LSD ($P \leq 0.05$).

ments above drilling fluids on the Mertz site (Table 1). In the 0 to 15-cm increment, EC values in the 30- and 150-cm burial treatments increased significantly over time, and a similar trend was observed in the 90-cm treatment. The 90-cm + barrier treatment significantly decreased the extent of upward salt migration compared to other burial treatments after 44 months. At 15 to 30 cm electrical conductivities in the 90- and 150-cm burial treatments increased significantly over time and were greater than those in the 30-cm and 90-cm + barrier treatments. Salt migration from drilling fluids into the 30 to 60-cm increment occurred only in the 150-cm burial treatment.

Patterns of salt movement from drilling fluid into overlying soil were somewhat different on the Weatherby study site. Mean soil EC values in the 0 to 15-cm increment above the drilling fluid ranged from 16.4 to 23.6 ds m^{-1} after 44 months, but differences were not significant (Table 1). Averaged over depth of burial, electrical conductivities in the 15 to 30-cm increment increased significantly over time from 3.9 to 18.2 dS m^{-1}. The greatest EC values occurred in the 90- and 150-cm burial treatments (37.3 and 17.4 dS m^{-1}, respectively). Nevertheless, mean EC values of 10 dS m^{-1} in the surface 15 cm of the 30-cm burial treatment would reduce seedling establishment and yield of many non-salt-tolerant plant species (U.S. Salinity Laboratory Staff 1954). The time x treatment interaction was significant for EC values in the 30 to 60- cm increment. Both the 90- and 150-cm burial depths exhibited significant increases in EC values from 20 to 44 months. The capillary barrier did not decrease average EC values in the 0 to 15- and 15 to 30-cm increments. Failure of the limestone material used at this site to provide an effective barrier at the soil-drilling fluid interface was also evident after 20 months (McFarland et al. 1992a). However, the capillary barrier did limit salt movement into the 30 to 60-cm increment and resulted in significantly lower EC values compared to other burial depths. There was no evidence of salt movement above the 30 to 60-cm increment on either study site.

Time and the time x depth of burial interaction were significant for ESP values in the 0 to 15- and 15 to 30-cm increments, respectively, at the Mertz site (Table 2). Averaged over depth of burial, ESP values in the 0 to 15-cm increment increased significantly over time from 5.7 to 13.6 after 44 months. The capillary barrier did not significantly reduce soil exchangeable Na^{+} in this increment. Conversely, ESP values at 15 to 30-cm above drilling fluid in the 30- and 90-cm+ barrier treatments were <1 and were significantly less than those in the 90- and 150-cm treatments (5.1 and 6.9, respectively). Significant increases in ESP values in the 90 and 150-cm treatments over time corresponded with greater EC values in these treatments (Table 1).

Exchangeable sodium percentages in the 0 to 15- and 15 to 30-cm increments on the Weatherby site increased significantly over time (Table 2). Depth of burial did not significantly affect ESP values, although the smallest increases were observed in the 90-cm + barrier treatment in both increments. No significant treatment effects on ESP values were observed in soil increments >30 cm above buried drilling fluids on either study site.

Depth of burial did not affect upward salt migration. However, increases in EC and ESP values in the 15 to 30-cm increment of the shallow, 30-cm treatment tended to be less than those observed for greater depths of burial. Data collected during the first 20 months of this study showed that temporal fluctuations in soil water content were greatest for the 30-cm burial treatment (McFarland et al. 1992a). Assuming similar patterns of water movement during the second evaluation period, this likely accounts for reduced EC and ESP values in the shallow burial treatment after 44 months. Since soluble salts tend to move with the wetting front, they are often temporarily leached from the surface soil zone by rainfall. These fluctuations are less substantial or absent at greater depths where more consistent patterns of salt movement and accumulation were observed. Considerable additional salt migration since the 20-month evaluation, particularly into the 30 to 60-cm increment above buried drilling fluid, suggests that an "equilibrium" condition may not yet have been achieved with respect to upward salt movement.

Site differences with respect to the degree of salt movement were attributed to greater effects of high salt concentrations on soil hydraulic properties, primarily as a result of differences in clay type and content. The Mertz site had a higher clay content and contained a greater percentage of expanding clays than the Weatherby site. In Na-affected soils, swelling of clay particles reduces soil pore size, and movement of clay platelets as a result of clay dispersion further blocks pores. Saturated hydraulic conductivity generally decreases as salt concentration decreases or as ESP increases. The effect is usually greatest for soils with high contents of swelling minerals and those with high clay contents (Bresler et al. 1982).

Analyses of the drilling fluids used indicated that Ba, Cr, Cu, Ni and Zn occurred in concentrations greater than those in the native soils (McFarland et al. 1992a). Analyses of soil samples collected from the 0 to 15-cm zone above drilling fluid 1 and 20 months after pits were covered showed no evidence of upward movement of these metals over time. Soil analyses after 44 months also showed no upward movement of these metals (data not shown). Little or no movement of these metals would be expected in alkaline, calcareous soils due to sorption and/or precipitation reactions which immobilize them in or near the waste/soil interface.

Plant Growth and Chemical Composition

Survival of fourwing saltbush transplants after 44 months ranged from 92 to 100%, and depth of drilling fluid burial did not significantly affect saltbush survival. Spread and overlap of stolons of buffalograss transplants prevented measurement of individual transplant survival, but there were no indications of additional plant mortality after 44 months.

Similar to the 17-month evaluation, canopy cover of fourwing saltbush transplants 44 months after planting was significantly greater on plots with buried drilling fluids (45 to 76%) compared to control plots (22 to 32%) at both study sites (Table 3). This difference was attributed to the tillage effect associated with pit construction, which was also observed to improve initial plant growth and establishment (McFarland et al. 1992b). However, average canopy cover of fourwing saltbush on the 30-cm treatment on the Mertz site was significantly less than on other treatments with buried drilling fluid. A similar trend was observed for buffalograss on both sites, although differences were not significant. Fourwing saltbush canopy cover had increased by 6 to 20% during the preceding 2 years, while buffalograss canopy cover had decreased on most plots by 3 to 11%. Regression equations for estimating total aboveground biomass of fourwing saltbush were: $\log W = -5.024 + 0.918 [\log (4\pi r^3/3)]$ for the Mertz site, and $\log W = -7.660 + 1.063 [\log (\pi r^2 h)]$ for the Weatherby site, where r is the average plant canopy radius in cm, h is plant height in cm, and oven-dry weight (W) is expressed in grams. These equations accounted for 89 and 97% of the variability in aboveground biomass for fourwing saltbush at the Mertz and Weatherby sites, respectively.

Fourwing saltbush biomass production was significantly greater on treated plots (11,450 to 21,501 kg ha^{-1})compared to control plots (1,749 to 4,184 kg ha^{-1}) after 44 months (Table 3). This corresponded with results observed at 17 months, although saltbush yields had increased by 561 to 14,261 kg ha^{-1}, and was similarly attributed to the tillage effect caused by pit construction. Yields of fourwing saltbush at the Mertz site on plots with drilling fluids buried 30 cm were significantly less than those on the 150-cm burial treatment. This response was not observed on the Weatherby site, most likely because of differences in soil type and clay content. The greater percentage of expanding clays at the Mertz site facilitated increased clay dispersion. Subsequent reductions in oxygen diffusion and infiltration of water may have been primary factors in limiting plant growth

Table 3. Average canopy cover and biomass production of fourwing saltbush and buffalograss transplants 44 months after planting on the Mertz and Weatherby study sites as influenced by depth of drilling fluid burial.

	Mertz study site		Weatherby study site	
Depth of burial	Saltbush	Buffalograss	Saltbush	Buffalograss
(cm)				
	Canopy cover (%)			
Control	22a*	6	32a	12
30	45b	10	76b	14
90	64c	16	62b	24
90 + barrier	62c	14	65b	23
150	60c	20	67b	24
	Biomass (kg ha^{-1})			
Control	1749a	115	4184a	301
30	12822b	101	16464b	226
90	17884bc	231	11450b	555
90 + barrier	18826bc	381	13000b	345
150	21501c	372	12433b	278

* Means within a parameter and column followed by similar lower case letters are not significantly different according to Duncan's new multiple range test ($P \leq 0.05$).

Table 4. Concentrations of Na, K, Ca and Mg in fourwing saltbush and buffalograss tissue 44 months after planting on the Mertz and Weatherby study sites as influenced by depth of drilling fluid burial.

	Mertz study site			Weatherby study site		
	Fourwing saltbush			Fourwing saltbush		
Depth of burial	Leaf	Stem	Buffalo-grass	Leaf	Stem	Buffalo-grass
(cm)	(g kg^{-1})					
	(Na)					
Control	0.18	0.04b*	0.03	0.11ab	0.03	0.03a
30	0.12	0.02a	0.05	0.14b	0.04	0.07b
90	0.11	0.02a	0.04	0.09a	0.03	0.05ab
90 + barrier	0.10	0.02a	0.04	0.10ab	0.03	0.05ab
150	0.10	0.02a	0.04	0.08a	0.03	0.04a
	(K)					
Control	44.6a	12.8	3.5	45.6a	16.3	4.4
30	52.3ab	12.5	3.7	63.7b	16.1	3.9
90	61.6bc	13.7	3.7	60.5b	15.6	4.3
90 + barrier	60.3bc	13.8	3.7	59.2b	18.1	4.7
150	63.7c	12.6	4.3	61.8b	16.6	4.4
	(Ca)					
Control	36.9b	10.2	7.7	35.3b	8.4c	8.8
30	23.6a	5.7	8.3	21.4a	5.2a	14.0
90	22.0a	5.3	8.5	21.2a	5.3ab	11.6
90 + barrier	19.5a	5.3	8.5	24.7a	6.6b	11.5
150	22.5a	4.8	7.7	20.3a	5.3ab	13.2
	(Mg)					
Control	6.6	2.0	1.3	9.9c	2.5	1.1
30	7.1	1.7	1.3	7.5a	2.0	1.6
90	6.6	1.7	1.4	8.6ab	2.1	1.3
90 + barrier	6.1	1.7	1.1	9.0bc	2.4	1.4
150	6.4	1.6	1.2	10.0c	2.3	1.5

* Means within an element and column followed by similar lower case letters are not significantly different according to Duncan's new multiple range test ($P \leq 0.05$).

on the Mertz site. This would explain the observed differences in plant growth even though root zone salinities in the 30-cm depth of burial treatment were greater on the Weatherby site.

Buffalograss yields were not affected by depth of drilling fluid burial (Table 3). However, biomass production in the fourth growing season was 12 to 75% less than that after 2 growing seasons (McFarland et al. 1992b). In contrast to fourwing saltbush, lower yields of buffalograss were attributed to the combined effects of shallow rooting of this species and below average rainfall received during the 1989 growing season.

Sodium concentrations in buffalograss growing on the 30-cm treatment on the Weatherby site were significantly greater than those in buffalograss growing on control or 150-cm burial treatments (Table 4). Saltbush leaves from 30-cm burial treatments on the Weatherby site also contained more Na than those from plots with drilling fluids buried 90 or 150 cm. In contrast, there was no evidence of elevated Na concentrations in either species on plots with buried drilling fluid at the Mertz site. These site differences were likely attributable to greater upward salt migration at the Weatherby site (Tables 1 and 2). The elevated Na concentrations in buffalograss at the Weatherby site were similar in magnitude to those observed 17 months after planting (McFarland et al. 1992b). Thus, although additional upward salt movement occurred after 44 months, accumulations in plant tissue remained relatively constant.

Table 5. Concentrations of Ba, Cr, Cu, Ni and Zn in fourwing saltbush and buffalograss tissue 44 months after planting on the Mertz and Weatherby study sites as influenced by depth of drilling fluid burial.

	Mertz study site			Weatherby study site		
	Fourwing saltbush			Fourwing saltbush		
Depth of burial	Leaf	Stem	Buffalo-grass	Leaf	Stem	Buffalo-grass
(cm)			(mg kg^{-1})			
			(Ba)			
Control	74.9	38.6b*	46.5	55.2b	20.3	45.0
30	47.8	18.0a	39.5	42.5ab	15.8	49.2
90	50.0	23.1a	44.3	48.2b	20.9	50.5
90 + barrier	43.7	19.6a	41.7	53.1b	21.5	52.6
150	48.9	19.7a	39.1	32.7a	13.7	52.4
			(Cr)			
Control	6.1	3.6	2.0	6.0	4.2	4.1
30	5.7	3.1	1.9	4.3	1.7	7.1
90	5.1	3.2	1.7	7.4	3.8	6.6
90 + barrier	6.5	3.0	1.6	6.3	4.2	4.9
150	5.4	2.8	2.1	4.2	2.8	5.2
			(Cu)			
Control	10.4	4.8a	8.1	9.2	5.1	6.5
30	12.1	5.8b	6.1	13.5	6.4	7.3
90	12.8	5.7b	5.2	13.9	6.0	7.3
90 + barrier	12.6	5.9b	5.6	11.1	5.7	7.8
150	13.7	5.8b	5.8	13.2	5.4	7.2
			(Ni)			
Contro	5.1	3.4	1.8	8.3	4.7	1.9
30	3.2	3.8	1.4	8.0	2.2	2.2
90	4.1	2.9	1.0	8.0	5.5	1.6
90 + barrier	5.8	1.5	1.7	5.9	4.6	1.9
150	5.0	3.9	1.8	8.6	4.8	1.7
			(Zn)			
Control	18.4	8.8	51.3	17.9	9.6a	50.2
30	38.9	17.4	35.7	24.7	14.0b	44.1
90	37.8	16.0	37.9	28.4	14.2b	55.9
90 + barrier	41.0	18.9	35.5	32.7	14.9b	54.1
150	41.5	17.6	37.3	37.4	13.9b	49.3

*Mean within an element and column followed by similar lower case letters are not significantly different according to Duncan's new multiple range test ($P \leq 0.05$).

Concentrations of K in fourwing saltbush leaves growing on control plots at both locations were significantly less than those in plants growing on most plots with buried drilling fluids (Table 4). In contrast, concentrations of Ca in fourwing saltbush leaves growing on control plots at both locations, and in saltbush stems growing on control plots at the Weatherby site were significantly greater than those in plants growing on plots with buried drilling wastes. Since these results tended to be consistent for treated plots versus control plots, they were attributed to residual effects of pit construction on plant growth (tillage effect) and nutrient availability (soil profile mixing), rather than to the direct effect of buried drilling fluids. Concentrations of Mg in saltbush leaves on control plots were greater than those on plots with drilling fluids buried 30 and 90 cm deep on the Weatherby lease.

Concentrations of Na in buffalograss and fourwing saltbush tissues in this study (0.02-0.18 g kg^{-1}) were less than the dietary requirements for Na in livestock (~ 2 g kg^{-1}), and thus would pose no potential toxicity problem (National Research Council 1980). Concentrations of K, Ca, and Mg in buffalograss and saltbush stems were below the maximum tolerable dietary levels for livestock. In contrast, fourwing saltbush leaves grown on control plots and most plots with buried drilling fluids contained concentrations of K, Ca, and Mg greater than maximum tolerable dietary levels for livestock (K 30 g kg^{-1}; Ca 20 g kg^{-1}; Mg 5 g kg^{-1}) (National Research Council 1980). Other researchers have reported very high concentrations of Na (0.9- 32 kg^{-1}), K (21-69 g kg^{-1}), Ca (7-13 g kg^{-1}), and Mg (6-9 g kg^{-1}) in fourwing saltbush (Smit and Jacobs 1978, Richardson 1982, Khalil et al. 1986). Our data suggest that the population of fourwing saltbush used in this study was a low-sodium biotype that excludes Na but absorbs large amounts of K (Richardson 1982). The high K, Ca, and Mg concentrations in fourwing saltbush leaves would not be expected to cause toxicity problems under normal range conditions because the shrub is not highly palatable and usually comprises only a small proportion of the total diet of livestock.

There was no evidence of increased absorption of Ba, Cr, or Ni by fourwing saltbush or buffalograss on plots with buried drilling fluids compared to control plots, and only limited evidence of increased uptake of Cu and Zn (Table 5). Concentrations of Cu (Mertz site) and Zn (Weatherby site) were greater in saltbush stems on plots with buried drilling fluids compared to the controls, as was observed 20 months after the drilling fluids were buried (McFarland et al. 1992b). However, the absence of a significant depth of burial effect suggests that differences were due to the influence of soil disturbance on plant utilization of native soil Cu and Zn, rather than uptake of metals contained in the drilling fluids. In contrast, total Ba concentrations in fourwing saltbush leaves were significantly lower on most plots with buried drilling fluids compared to control plots (Table 5). Concentrations of Ba in buffalograss and saltbush tissues were within the range reported for other plant species (Nielsen 1986). Levels of soluble Ba should not exceed 20 mg kg^{-1} in livestock diets, but much of the Ba present in plant material is not biologically available and is of little concern (National Research Council 1980). Concentrations of Cr, Cu, Ni, and Zn in buffalograss and fourwing saltbush tissues were well below the maximum tolerable dietary levels for livestock (Cr 1,000 - 3,000 mg kg^{-1}; Cu >25 mg kg^{-1} for adult sheep, >100 mg kg^{-1} for adult cattle; Ni 50 mg kg^{-1}; Zn 300 - 500 mg kg^{-1}) (National Research Council 1980).

Conclusions

Burial of spent drilling fluids in arid and semiarid environments is a viable alternative to the conventional method of surface disposal.

Soluble salt migration as much as 30 to 60 cm into soil overlying drilling fluid had occurred after 44 months. However, adverse effects on plant growth were observed only with shallow, 30-cm burial and were restricted to soils with higher clay contents. Increases in plant tissue salt concentrations indicated that uptake of drilling fluid constituents may occur with shallow burial, but heavy metals will not be available to plants under the conditions reported here. Selective-placement burial of drilling fluids reduces the rate and extent of soil contamination on drilling sites, and should facilitate natural or artificial revegetation.

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