Biogeochemical Variability of Plants at Native and Altered Sites, San Juan Basin, New Mexico

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1134-D

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By L. P. GOUGH and R. C. SEVERSON

GEOCHEMICAL SURVEY OF THE WESTERN ENERGY REGIONS

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Regional background concentrations of elements in native plants and a discussion of soil-plant relationships are given for an area of increasing energy development

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Doyle G. Frederick, *Acting Director*

Library of Congress Cataloging in Publication Data
Gough, L. P.
Biogeochemical variability of plants at native and altered sites, San Juan Basin, New Mexico.
(Geochemical survey of the western energy regions)
(Geological Survey Professional Paper 1134-D)
Supt. of Docs. no.: I 19.16:1134-D
Bibliography: p. 25
1. Botany–New Mexico–Variation. 2. Botany–San Juan River watershed (Colo.-Utah)
3. Plant-soil relationships–New Mexico. 4. Plant-soil relationships–San Juan River watershed (Colo.-Utah)
5. Plants-Chemical analysis. 6. Soils–New Mexico. 7. Soils–San Juan River watershed (Colo.-Utah)
8. Coal mines and mining–Environmental aspects–New Mexico. 9. Reclamation of land–Environmental aspects–New Mexico. 10. San Juan River watershed (Colo.-Utah)
I. Severson, R. C. (Ronald Charles), 1945- II. Title. III. Series. IV. Series: Geological Survey Professional Paper 1134-D.
QK176.G68 581.9789 81-607946 AACR2

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

TABLES

GEOCHEMICAL SURVEY OF THE WESTERN ENERGY REGIONS

BIOGEOCHEMICAL VARIABILITY OF NATIVE AND ALTERED SITES, SAN JUAN BASIN, NEW MEXICO

By LARRY P. GOUGH and R. C. SEVERSON

ABSTRACT

The San Juan Basin is becoming a major energy resource region. The anticipated increase in strip mining for coal can be expected to alter the geochemical and biogeochemical environment, because such activities destroy the native vegetation communities, rearrange the rock strata, and disrupt natural soil development. This study investigated the variability in the biogeochemistry of native plant species at both undisturbed and altered sites and assessed the importance of the observed differences. Three studies are involved in this investigation: Study 1, the biogeochemical variability of native species found at sites throughout that part of the basin underlain by economically recoverable coal; Study 2, the biogeochemical variability of native species growing on soils considered favorable for use in the topsoiling of spoil areas; and Study 3, the biogeochemical variability of native species on rehabilitated sites at the San Juan coal mine.

Summary statistics for concentrations of 35 elements (and ash yield) are reported in Study 1 for galleta grass, broom snakeweed, and fourwing saltbush. The concentrations of manganese, molybdenum, nickel, and uranium (and possibly iron and selenium) in galleta show regional patterns, with the highest values generally found in the south-central region and western edge of the study area. Differences in the concentration of elements between species was generally subtle (less than a factor of two) except for the following: ash yield of saltbush was two times that of the other plants; boron in snakeweed and saltbush was four times greater than in galleta; iron in galleta was two times greater than in saltbush; and, calcium, magnesium, potassium, phosphorus, and sulfur were generally highest in saltbush.

Summary statistics (including the 95-percent expected range) for concentrations of 35 elements (and ash yield) are reported from Study 2 for galleta and broom snakeweed growing on the Sheppard, Shiprock, and Doak soil association. Significant regional (greater than 10 km) variation for aluminum, iron, sulfur, vanadium, and zirconium in galleta are reported; however, for most elements, a significant proportion of the variation in the data was measured locally (less than 0.1 km). This variation indicates that samples of galleta and snakeweed taken more than 10 km apart vary, in their element composition, little more than plants sampled as close together as 0.1 km.

The concentrations of 35 elements (and ash yield) in alkali sacaton and fourwing saltbush, which were collected on a rehabilitation plot at the San Juan mine (Study 3), are compared with those of control samples of similar material from native sites from throughout the San Juan Basin. Concentrations of aluminum, arsenic, boron, cobalt, copper, fluorine, iron, lead, manganese, sodium, and uranium in samples of saltbush growing over spoil generally exceed the levels of these elements in control samples. For many elements, concentrations in mine samples are from two to five times higher than concentrations in the control samples. Sodium concentrations in saltbush, however, were 100 times higher in mine samples than in control samples. This high concentration reflects a corresponding 100-fold increase in the extractable sodium levels in spoil material as compared to C-horizon control samples. Sampled plants from the mine area, spaced relatively close together (5 m (meters) or less), vary greatly in their element compositions, apparently in response to the heterogenous composition and element availability of the mine soils. Topsoiling to a depth of 20 cm (centimeters) does little to ameliorate the uptake of elements from spoil by saltbush.

INTRODUCTION

LOCATION OF THE STUDY AREA

The study area is in the San Juan Basin of northwestern New Mexico and was confined to the area containing strippable coal deposits. Specifically, this is a 38,000 km^2 (square kilometer) area, approximately bounded by 35°–37° N latitude and 107°–109° W longitude, that includes parts of McKinley, Rio Arriba, Sandoval, and San Juan Counties. The Dakota Sandstone, the Menefee Formation of the Mesaverde Group, and the Kirtland Shale and Fruitland Formation[1], all of Late Cretaceous aage (Dane and Bachman, 1965), contain coal; however, the thickest and most economically recoverable coal seams are in the Kirtland Shale and Fruitland Formation (Shomaker and others, 1971). These authors stated that within the San Juan Basin, the Kirtland Shale and Fruitland Formation contain more than 90 percent of the strippable coal deposits, which are defined as having less than 76

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[1] Although we refer to the coal deposits of the Kirtland Shale and Fruitland Formation, we realize that the most significant deposits are in the Fruitland Formation.

m of overburden. Fassett and Hinds (1971) estimated that the Kirtland Shale and Fruitland Formation have a total reserve, within New Mexico, of about 180 billion (1.8×10^{11}) t (metric tons), and about 11 billion t are overlain by less than 150 m of overburden. The Navajo coal field, in the Kirtland Shale and Fruitland Formation, is southwest of Farmington, within the Navajo Indian Reservation, and is the location of Utah International Inc.'s Navajo mine, the largest coal strip mine in the State. South of the Navajo mine there are two vast leases of near-surface coal nearing development. The coal from the Navajo field is predominantly used onsite by the 2,000 MW(e) (megawatts of electricity) Four Corners powerplant. Another mine-mouth operation is northwest of Farmington in the Fruitland coal field. Here Western Coal Co.'s San Juan mine supplies coal to the 328 MW(e) San Juan generating station. A recent estimate for coal production in San Juan County, for 1980 and 1990, is 12.5 and 18.9 million t, respectively (U.S. Department of Energy, 1980). All of this coal is low in sulfur (less than 0.7 percent), is subbituminous, and yields 8,500 to 10,500 BTU per pound.

The west, southwest, and south parts of the basin contain deposits of strippable coal (to the east the coal is too deep and dips too steeply to be strip mined), and other parts of the basin contain vast reserves of oil and natural gas (Barnes and Arnold, 1951) and uranium (Hilpert, 1969). This region, therefore, is extremely rich in energy resources, and the development of these resources is accelerating as demand for domestically produced fuels increases. Energy-related impacts on this region will include mining, conversion, and transport of coal; mining and processing of uranium ore; extraction and refining of oil and gas; and ultimately, the gasification and perhaps liquification of coal. By the year 2000, therefore, hundreds of square kilometers of land in the San Juan Basin will have been altered by activities associated with energy development.

PHYSICAL FEATURES OF THE STUDY AREA

The San Juan Basin is in the southeastern part of the Colorado Plateaus physiographic province (Fenneman, 1931). Drainage of the moderately to highly dissected basin is toward the west via the perennial San Juan River and its tributaries. The southern part of the basin is drained by the intermittent Chaco River and its tributaries, which flow north to the San Juan River. The elevation of that part of the basin underlain by Cretaceous rocks ranges from about 1,500 to 2,200 m and is characterized by broad plains occasionally broken by abrupt basaltic dikes and hogbacks (fig. 1) but more commonly by sandstone-, shale-, and clinker-capped buttes and mesas. Unstable sand dunes, rolling hills, badlands, pediment surfaces and dry arroyos are also common landscape features. The climate profile given by U.S. Department of the Interior (1976) for the region essentially covered by the Study 2 area is summarized as follows: winds are generally from the southeast in winter and from west to east in spring and summer; the highest sustained velocities are in the summer. Precipitation is from 14 to 21 cm annually depending on elevation and position relative to the rain-shadow effects of the Chuska Mountains on the west, and season (summer is wetter than winter; spring and fall are dry); evaporation is 130 cm annually at Farmington. Monthly maximum mean temperatures (F) are (U.S. Department of the Interior, 1976, p. 5): January, 29; February, 35; March, 41; April, 51; May, 59; June, 70; July, 76; August, 73; September, 66; October, 54; November, 40; and December, 30.

FIGURE 1. — Typical landscape in the southeastern part of the San Juan Basin showing broad plains (foreground) that are interrupted by occasional volcanic necks and dikes (background). Galleta grass was found interspersed among the dominant fourwing saltbush. Soils were of the Turley series (Typic Torriorthent, fine loamy, mixed (calcareous), mesic), having developed in alluvium.

The vegetation of the San Juan Basin is characteristic of North American continental desert regions whose summer temperatures are moderated by a relatively high elevation and winter temperatures by relatively low latitude. Soil types strongly influence both the areal distribution of plants and the floristic composition of the vegetation. For example, shallow soils that develop over shale have very low permeability, are high in clay, and are usually saline. This condition results in essentially barren areas. Deep sandy soils, however, are permeable and support a diverse vegetation. Grazing pressure (in places severe), aspect (direction of slope), and local edaphic and topographic extremes also contribute to a complex vegetation mosaic. Depending on individual sites, therefore, any of the following species may dominate:

Grasses

Bluteloua gracilis	blue grama
Hilaria jamesii	galleta
Muhlenbergia torreyi	ring muhly
Oryzopsis hymenoides	indian ricegrass
Sporobolus airoides	alkali sacaton
S. cryptandrus	sand dropseed

Shrubs and Trees

Artemisia tridentata	big sagebrush
Artiplex canescens	fourwing saltbush
A. confertifolia	shadscale
Ephedra torreyana	Torrey ephedra (jointfir)
Gutierrezia sarothrae	broom snakeweed
Juniperus spp.	juniper
Pinus edulis	pinon
Sarcobatus vermiculatus	greasewood
Chrysothamnus nauseosus	rabbitbrush

REASONS FOR THE STUDY

Lands altered as a result of the activities of strip mining must now be rehabilitated according to specific guidelines and regulations. In New Mexico, rehabilitation of mined lands and rehabilitation research (Aldon and Springfield, 1975) began in 1972 with the passage of the New Mexico Coal Surface Mining Act. The establishment of long-term plant cover and eventual ecosystem stabilization is the first concern of rehabilitation. Initially, plot studies are conducted on different plant species and ecotypes for their ability to successfully germinate, grow, and reproduce under the sometimes severe arid conditions that characterize sections of the San Juan Basin (Aldon and Springfield, 1975). Once these plants are identified and cover is achieved on favorable sites, work shifts to specific mine sites having peculiar overburden characteristics that severely affect, for one reason or another, the establishment of desirable species. Such studies seek to identify specific properties that make altered substrates either toxic or deficient in some essential property for normal plant growth (Gould and others, 1975, 1977). This type of work leads to new methods that ameliorate the effects of the undesirable property. We have attempted, in this and similar studies (Gough, Severson, and McNeal, 1979), to provide background concentration levels for a large number of elements in native-plant species likely to be utilized in rehabilitation work. Problems associated with geochemical alterations in soils, spoils, and rehabilitation species were discussed by Erdman (1978) and through time may prove just as troublesome as the problems associated with achieving acceptable plant cover.

This study had the following objectives: (1) To evaluate the natural spatial variability in the element content of selected native species growing over the Cretaceous coal deposits of the Mesaverde Group and the Fruitland Formation. This is the area most likely to be directly affected by the surface mining of coal. (2) To evaluate the natural spatial variability in the element content of selected native species growing in Sheppard, Shiprock, and Doak soils. From the data presented by Maker, Folks, Anderson, and Link (1973) and Maker, Keetch, and Anderson (1973), these substrates are inferred to be the most desirable native soils for stockpiling and respreading over rehabilitation sites. Because the Fruitland Formation coals are of greatest nterest, our sampling sites were restricted to appropriate soil types that have developed over this formation. (3) To evaluate the variability in the element content of rehabilitation species growing on revegetated mine sites and to compare the biogeochemistry of rehabilitation plants to native plants.

The results from this study include: (1) observed ranges and calculated baseline-concentration ranges for as many as 35 elements in four native-plant species; 2) an assessment of varying distance increments at which significant proportions of the total variability occur in the concentration of elements in two native-plant species growing in a defined soil association; (3) a comparison of the element content of plants growing on native and geochemically altered sites; (4) an assessment of the forage quality of selected species growing on native and altered sites; and (5) a discussion of soil-plant element relations at both native and altered sites.

We use the format of Severson and Gough (1981) and refer to that part of the study dealing with native plants collected in the broad region most likely to be affected by energy development as Study 1; reference to work on plants growing on the Sheppard, Shiprock, and Doak soil series is labeled Study 2; and reference to studies at the San Juan mine is called Study 3.

ACKNOWLEDGMENTS

We appreciate the diverse assistance from many ndividuals that made this study possible. The plant samples were washed by J. J. Dickson and M. P. Pantea, and were ashed and chemically analyzed by B. L. Bolton, T. F. Harms, K. E. Horan, C. S. E. Papp, S. E. Prelipp, and Michele Tuttle. R. W. Allen, manager of the Western Coal Co., kindly gave us access to the San Juan mine, and W. L. Gould, D. J. Leman, and J. A. Ferraiuolo of New Mexico State University allowed us to collect samples from their San Juan mine rehabilitation plots. W. L. Gould also reviewed this manuscript and shared with us unpublished information. The orientation to the region given us by Monte McClendon of the U.S. Bureau of Land Management proved invaluable. We acknowledge with gratitude the cooperation of Peter MacDonald and the Navajo Tribal Council for giving us sampling privileges on the Navajo Nation lands in New Mexico.

METHODS

FIELD

In July and August 1977 we sampled various grasses and shrubs, along with supporting A and C horizons of soil, at sites throughout the western, southwestern, and southern parts of the San Juan Basin in northwestern New Mexico. The grasses included the leaves, culms, and inflorescences of alkali sacaton (*Sporobolus airoidese* (Torr.) Torr.) and the entire plant (leaves, culms, inflorescences, rhizomes, and roots) of galleta grass (*Hilaria jamesii* (Torr.) Benth.). The shrub material consisted of the terminal 10–20 cm of stems with accompanying leaves of fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) and the whole aboveground parts (stems, leaves, and inflorescences) of broom snakeweed (*Gutierrezia sarothrae* (Pursh) Britt. & Rusby). Fourwing saltbush is dioecious, and our collections are a mixture of both male and female shrubs. None of the samples from female shrubs included the seeds because on some shrubs the seeds were so abundant that, had they been included, they would have dominated the sample. Except for the galleta samples, which consisted of numerous individuals commonly collected from a 10 or more square meter area, the samples were taken from one plant. Voucher specimens of each species are stored in the herbarium of the U.S. Geological Survey in Denver, Colo. Three separate studies were conducted, Study 1, Study 2, and Study 3.

STUDY 1

Galleta, snakeweed, and saltbush were collected throughout that part of the basin most likely to be directly affected by the surface extraction of coal. This is the area underlain by the subbituminous coal-bearing Kirtland Shale and Fruitland Formation and by the undifferentiated Mesaverde Group (Dane and Bachman, 1965; Fassett and Hinds, 1971), all of Late Cretaceous age (fig. 2). Within this area, 48 sites for plant and soil sampling were randomly selected according to a five-level, unbalanced, nested-cell, analysis-of-variance design (Severson and Gough, 1981). This design utilized the strategic placement of eight cells, 50-km on a side, on the coal-bearing region. Within each 50-km cell all four 25-km cells were sampled. The design was unbalanced below the 25-km cell level so that only a few 5-km and 1-km cells were sampled in each 25-km cell. Figure 3 shows the location of each randomly selected site within the nested-cell design. Because of the absence of of appropriate plant species at many of the Study 1 sites, an analysis of variance of the plant element-content data was not performed. The following numbers of samples for each species were collected: galleta, 25; snakeweed, 18; and saltbush, 10 (fig. 3). These samples are independent from one another because they were collected at sites chosen in a random selection process.

STUDY 2

The Kirtland Shale and Fruitland Formation occur as a narrow crescent within the center of the San Juan

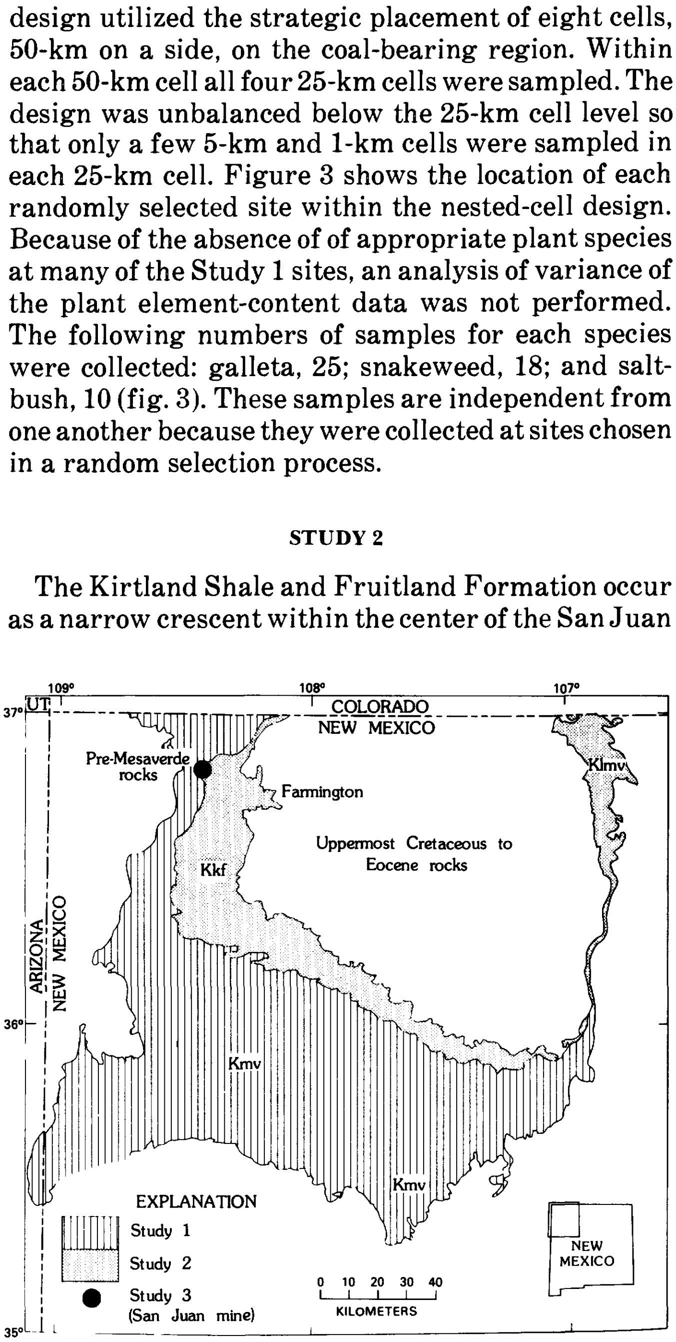


FIGURE 2. — Location of the three study areas within the San Juan Basin. Geology modified from Dane and Bachman (1965). Kkf, Kirtland Shale and Fruitland Formation; Klmv, Lewis Shale and Mesaverde Group; all of Late Cretaceous age. Units listed in order of increasing age.

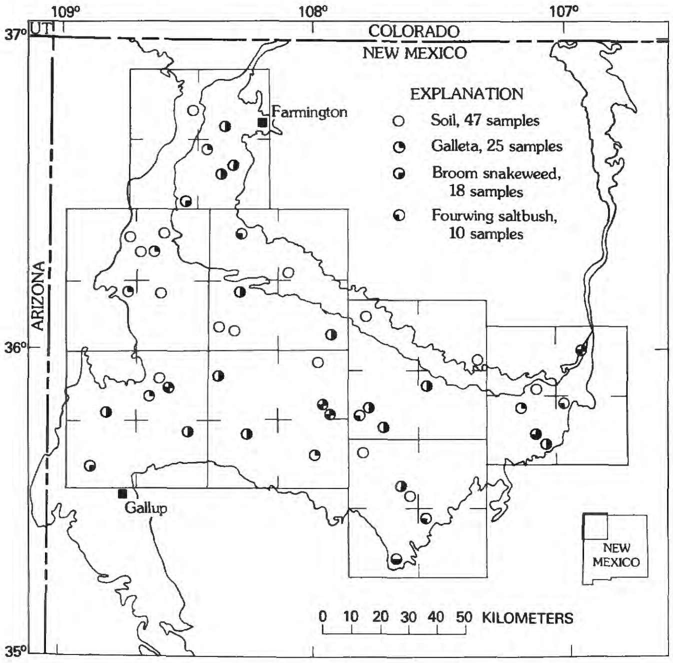


FIGURE 3. — Soil and plant sampling locations for Study 1 within the San Juan coal region with the unbalanced, nested, analysis-of-variance sampling grid superimposed.

Basin (figs. 2 and 4). Most of the economically recoverable coal is in the western half of this crescent, which extends for about 150 km from near the Colorado-New Mexico State Line in the north to near Cuba, N. Mex. in the southeast. Within this region, the Sheppard, Shiprock, and Doak soil series possesses physical (Maker, Folks, Anderson, and Link, 1973, and Maker, Keetch, and Anderson, 1973) and chemical (Severson and Gough, 1981) features favorable for native plant growth. Therefore, we consider these soils to be desirable for stockpiling for use in the rehabilitation of strip-mined lands. These soils are developed on stable (nondune) sands. This study, therefore, was confined to an examination of the element content of two common plants that occur on the major soil series within the area of outcrop of the Kirtland Shale and Fruitland Formation (fig. 5). Galleta and broom snakeweed were collected according to an unbalanced, nested, analysis-of-variance design of the "barbell-cluster" type described by Tidball and Ebens (1976). We divided the western part of the Kirtland Shale and Fruitland Formation into approximate 50-km segments and randomly located one barbell cluster within each of the three segments (fig. 4). The orientation of the major axis of the barbell depended on the width of the geologic unit studied and the extent of the Sheppard, Shiprock, and Doak soil series.

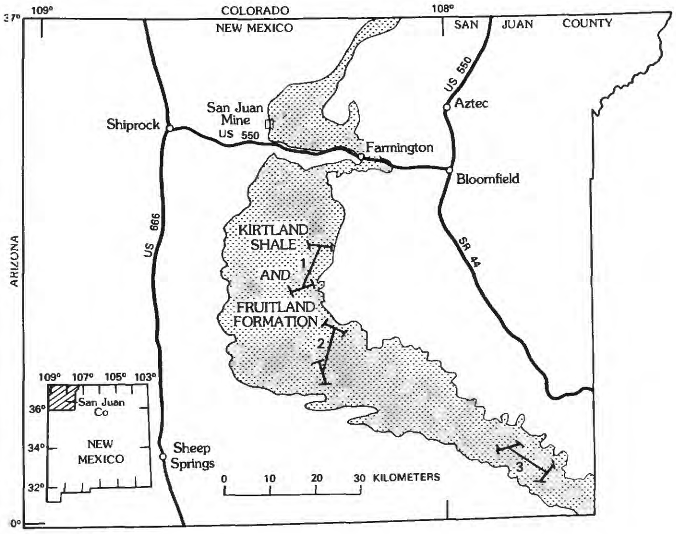


FIGURE 4. — Positions of the three barbell-cluster sampling areas for Study 2, San Juan County.

Each barbell cluster, like the one shown in Figure 6, consisted of a 10-km main axis. At each end of the main axis, a 5-km axis was oriented in a randomly selected direction. The next two smaller axes (1 and 0.1 km) were positioned at the ends of the 5-km axis in a like manner. Because of the unbalanced nature of the design, only 10 out of a possible 16 sites per barbell were targeted for sampling. Out of a total of 30 randomly selected sites we were able to collect 30 galleta samples and 27 fourwing saltbush samples. Unbalancing the design serves to economize field and laboratory expenses with little sacrifice in the reliability of the estimates of the variance components (Tidball, 1976; Miesch, 1976).

STUDY 3

The San Juan coal mine, which is operated by the Western Coal Co., is 23 km west-northwest of Farmington in San Juan County, N. Mex. (fig. 4). Subbituminous coal is mined from the Kirtland Shale and Fruitland Formation and supplied to the San Juan generating station nearby. The study site was in an area that had been mined, regraded, topsoiled (to a depth of about 20 cm), and seeded with fourwing saltbush and alkali sacaton in 1974. The rehabilitation site was not fertilized; however, straw mulch was crimped into the soil, and the area was periodically irrigated until the desired species became established (fig. 7).

In order to estimate local (less than 100-m) variation in the element content of reclamation species, we utilized a nested, unbalanced, analysis-of-variance design of the barbell-cluster type discussed above under Study 2. A single barbell was used and consisted of a

FIGURE 5. — Galleta grass stand in a big sagebrush-blue grama-grass dominated area of Study 2 that received little grazing pressure (markings on rod are in decimeter increments). Soils (Doak series, Typic Haplargid, fine loamy, mixed, mesic) in this area were characterized as being well drained.

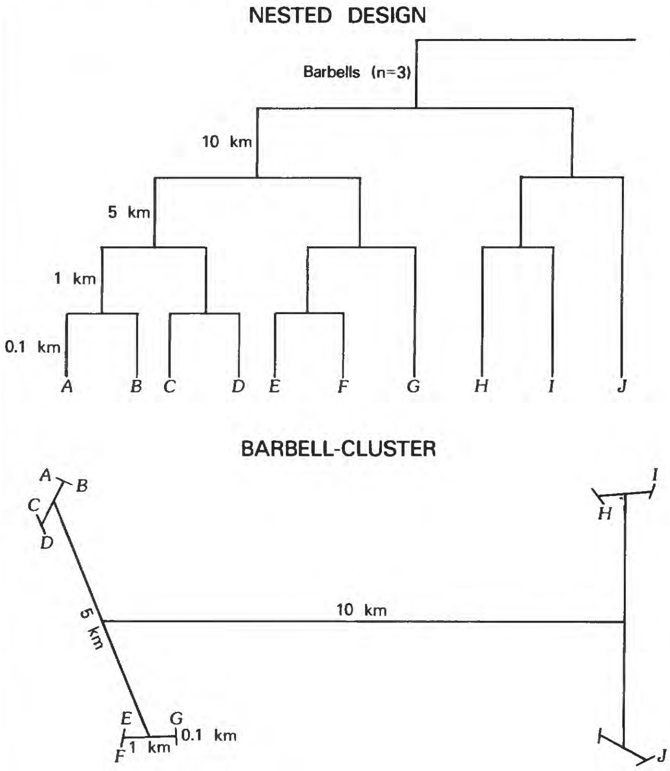


FIGURE 6. — Diagram of the unbalanced, nested, analysis-of-variance design used in Study 2. Sample sites are indicated by letters A through J.

main axis of 100 m; at the ends of the main axis were positioned the centers of two 25-m axes, and at the ends of the 25-m axes were positioned the centers of 5-m axes. By unbalancing the design we collected six out of a possible eight sites. As in Study 2, the orientation of each axis was determined by a random compass orientation.

LABORATORY

The sample preparation of the plant material for analysis from all three studies was the same. The samples were dried in a forced-air oven at 35°C and ground in a stainless steel mill to pass a 1.3-mm (millimeter) screen, and the homogenized ground material was either ashed by dry ignition at 500°C for 24 hours or by wet digestion (Harms, 1976). Because of excessive soil and dust contamination, samples of galleta, alkali sacaton, and snakeweed were washed prior to being dried and ground. This process consisted of many tap-water rinses (until the rinse water was free of visible suspended and settled material) followed by a single distilled water rinse. Ten percent of the samples were selected at random for splitting of the ground material and the analytical sequence of the entire suite of samples (plus splits) from all three studies was randomized. The analysis of blind splits provided a measure of laboratory precision, whereas the analysis of the samples in a randomized sequence insured that possible analytical bias would be converted to random error (Miesch, 1976). All element analyses were performed in the Denver laboratories of the U.S. Geological Survey by the methods listed in table 1.

SOIL SAMPLES

Chapter C of this series (Severson and Gough, 1981) and Crock and Severson (1980) detailed the sampling and analytical methods for soil materials in the San Juan Basin studies. A brief summary of these methods will aid the reader in following the discussions on soil-plant element relations in subsequent sections.

Samples of A- and C-horizon soils were collected throughout the basin in conjunction with the sampling

TABLE 1. — *Analytical methods and their approximate lower limits of determination for the plant materials sampled*

[All values are reported on an ash-weight basis, except where noted; LLD, lower limit of determination; ES, plate-reader emission spectrography; AA, flame atomic-absorption spectroscopy; SIE, selective ion electrode; FL-AA, flameless atomic-absorption spectroscopy; COLR, colorimetric; FLUR, fluorometric; TURB, turbidimetric]

Element	Analytical method	Approximate LLD (ppm)	Element	Analytical method	Approximate LLD (ppm)
Aluminum---	ES	200	Mercury[1]-------	FL-AA	0.01
Arsenic[1]---	AA	.05	Molybdenum-----	ES	2
Barium-----	ES	4.4	Nickel---------	ES	2
Boron------	ES	10	Niobium--------	ES	9.2
Boron------	ES	[2]500	Phosphorus-----	COLR	100
Cadmium----	AA	.4	Potassium------	AA	100
Calcium----	AA	100	Scandium-------	ES	2
Chromium---	ES	1	Selenium[1]------	FLUR	.01
Cobalt-----	AA	1	Sodium---------	AA	25
Copper-----	AA	1	Strontium------	ES	1
Europium---	ES	2	Sulfur (total)[1]	TURB	100
Fluorine[1]--	SIE	1	Titanium-------	ES	90
Iron-------	ES	200	Uranium--------	FLUR	.4
Lanthium---	ES	9.2	Vanadium-------	ES	2
Lead-------	ES	4.4	Ytterbium------	ES	.92
Lithium----	AA	4	Yttrium--------	ES	2
Magnesium--	AA	20	Zinc-----------	AA	1.0
Manganese--	ES	2	Zirconium------	ES	4.4

[1] Analyses determined on dry material not ash.

[2] Upper limit of determination.

FIGURE 7. — Site at the San Juan mine (Study 3) where plant and mine-soil samples were collected. Irrigation (pipe in middle ground) was used initially to establish vegetation in an area that was regraded and then topsoiled to a depth of about 20 cm. Isolated fourwing saltbush individuals and crimped straw containing alkali sacaton in seeded rows are visible.

of the plant material. At the San Juan mine, replaced topsoil and the underlying mine soil (to a depth of 50 cm) were also collected. In every instance, the soil samples were collected with a bucket auger adjacent to the plant (or group of plants) sampled.

In the laboratory, the samples were dried at ambient temperature, disaggregated, and sieved (10 mesh). Splits of the minus 2-mm material were further ground to minus-100 mesh and used for all total-element determinations. The disaggregated but unground minus 2-mm material was used for the extractable element determinations.

The extractable concentrations (in parts per million) of cadmium, cobalt, copper, iron, manganese, nickel, lead, and zinc were measured following the use of the chelate DTPA (0.005 *M* (molar) diethylenetriaminepentaacetic acid at a pH of 7.3) (Lindsay and Norvell, 1978). A water saturation extract was used for determining soluble concentrations (meq/L) (milliequivalents per liter) of calcium, magnesium, potassium, sodium, chloride, and sulfate, and a sodium-acetate extract was also used for exchangeable concentrations (meq/100g) (milliequivalents per 100 grams) of calcium, magnesium, potassium and sodium. Concentrations (in parts per million) of boron were determined in a hot-water extract. Standard methods (or calculations) were also used to determine the following additional soil chemical and physical properties: pH, cation-exchange-capacity (CEC), exchangeable-sodium-percentage (ESP), sodium-adsorption-ratio (SAR), specific conductance, and the relative amounts of sand, silt, and clay. A number of different methods were also used to determine the total concentration of the following elements and compounds in soil: aluminum, arsenic, boron, barium, beryllium, carbon, carbonate carbon, organic carbon, calcium, cobalt, chromium, copper, erbium, iron, germanium, mercury, potassium, lanthanum, lithium, magnesium, manganese, molybdenum, sodium, niobium, nickel, lead, rubidium, sulfur, scandium, silicon, tin, strontium, thorium, titanium, uranium, vanadium, yttrium, ytterbium, zinc, and zirconium.

STUDY DESIGN AND STATISTICAL ANALYSIS OF DATA

Frequency distributions for the element content of the plants studied were found to be strongly positively skewed, particularly the minor-essential and trace elements. A logarithmic transformation of such data adjusts the distribution curves so that they are more nearly normal. Therefore, statistical tests requiring the frequency distributions of the data to be normal are satisfied by this log transformation. Miesch (1976) gave additional information on the advantages of working with log-transformed geochemical data.

Because our data were transformed to logarithms, our summary statistics are reported as the geometric mean (GM) and geometric deviation (GD). For those elements that had censored values, the GM and GD were estimated using the technique of Cohen (1959). In Study 1, which did not utilize analysis of variance (AoV), the GD was calculated as the square of the logarithmic standard deviation. In Study 2 and Study 3, however, for those elements without censuring, the GD was calculated from the total variation as estimated by AoV, which accounts for the effects of the nested design. Total variation, as estimated by the square of the logarithmic standard deviation, is always smaller than total variation as estimated by the nested AoV design. For this study we have chosen to present the largest estimate of the GD; therefore, where wholly numeric data sets are involved (no censoring), and when an AoV calculation was made, the GD calculated from the AoV-estimated total variance is given.

Because the AoV procedure requires completely numeric data sets, all censored data were substituted with a real value equal to 0.7 times the lower limit of determination in ash, and 1.3 times the upper limit of determination. These multipliers are arbitrary fractions of the limit of determinations, and we assumed they would result in valid AoV results as long as censoring did not exceed one-third of the total number of values. If an element possessed more than one-third censoring, it was dropped from the study. The analysis of the data was performed on a computer using the U.S. Geological Survey's STATPAC library (Van-Trump and Miesch, 1977).

Plant-material concentration data, reported by the analyst to be on an ash-weight basis, were converted to a dry-weight basis prior to statistical analysis. This conversion was done because of the interest in dry-weight data by agronomists and others involved with reclamation studies.

The sampling designs used in this study have the advantage of maximizing biogeochemical information obtained from a limited sampling. Detailed discussions of the utility of the unbalanced, nested, analysis-of-variance design in geochemical studies were given by Tourtelot and Miesch (1975), Tidball (1976), Tidball and Ebens (1976), and Severson and Tidball (1979) and for biogeochemical studies by Erdman and others (1976) and Erdman and Gough (1977). The basic purpose of these AoV designs is to partition the total variation measured into at least two parts: a natural-variation component (using distance-related increments) and an analytical-error component. If the analytical error is significantly large for an element, relative to the natural variation, then it may not be economically feasibile to map the natural variation in the data. Many more samples would need to be collected or a more precise analytical method would have to be utilized in order to reduce this analytical variation to an acceptable level. However, if analytical variation is significantly small relative to natural variation, then it may be possible to construct a map showing this natural variation as differences in element concentration at some distance increment where there is a significant variance component. If natural variation is significant at all distance increments, then a map is impractical; the grand mean is a better estimate of a baseline value.

The Study 2 and Study 3 sampling designs permitted an estimation of the variation in the element content of the plants sampled at varying distance increments and, for Study 2, the variation due to analytical methods. The following statistical model was used in Study 2 to partition the variance, and it follows the hierarchial or "nested" case discussed in mathematical detail by Miesch (1976):

$$s^2_{\log x} = s^2_\alpha + s^2_\beta + s^2_\gamma + s^2_\delta + s^2_\epsilon + s^2_\zeta,$$

where the total observed logarithmic variance in the study area, for a given element concentration in either galleta grass or broom snakeweed, is represented by the term $s^2_{\log x}$ and is the sum of the estimates of six sources of variation. The factor s^2_α represents variability due to differences between the three barbell clusters at distances greater than 10 km (in these types of studies, called the "regional" component); s^2_β represents differences at 5-10 km; s^2_γ represents differences at 1-5 km; s^2_δ represents differences at 0.1-1 km; s^2_ϵ represents differences at less than 0.1 km (or the "local" component); and the last term, s^2_ζ, is composed of variation from sample preparation and analysis. The partitioning of the variance in Study 3 was similar:

$$s^2_{\log x} = s^2_\alpha + s^2_\beta + s^2_\gamma,$$

where the total observed logarithmic variance, in either fourwing saltbush or alkali sacaton, is represented by the term $s^2_{\log x}$ and is the sum of three components: s^2_α, variability at scales of 25-100 m; s^2_β, variability at scales of 5-25 m; and, s^2_γ, variability at scales greater than 5 m plus all other sources of variation including sample preparation and analysis.

RESULTS AND DISCUSSION

STUDY 1, BROAD AREAS MOST LIKELY TO BE AFFECTED BY ENERGY DEVELOPMENT

ECOLOGICAL NOTES ON THE SPECIES EXAMINED

GALLETA

The physiological ecology, taxonomy, and rangeland importance of galleta (*H. jamesii*) has been reviewed by West (1972). Galleta is a coarse perennial grass that revegetates predominantly by an extensive rhizome system. West (1972, p. 29) noted that "*Bouteloua gracilis* [blue grama] is probably the only grass of greater abundance and importance than *H. jemesii* throughout northern Arizona and New Mexico." He further stated that, although perhaps not preferred forage, galleta is often essentially the only grass available on many ranges and does make up a considerable proportion of the diet of cattle and sheep. Because of its economic importance, its resistance to drought, and its general hardiness once established, galleta appears to be an ideal candidate for use in mined-site rehabilitation. The only factor that prevents the general use of galleta, however, is the lack of an economical source of viable seed. W. L. Gould (written commun., 1980) reported that the seeds ripen gradually, from one end of the flower spike to the other, and upon ripening the seeds readily shatter. Consequently, only part of the seed crop can be harvested by combining a native stand. Further, the timing of the combining is critical because much of the seed shatters within a few days. High germination of seeds will occur in the field, however, if the palea and lemma are removed from the caryopsis during threshing and processing.

FOURWING SALTBUSH

This shrub, also called "chamiza" in New Mexico, is one of the most widely distributed western-American species of the Goosefoot Family. In the San Juan Basin it occurs in dry, moderately saline or alkaline sites where soil permeability is somewhat restricted. It occurs usually as scattered shrubs; however, extensive stands are found where it dominates the vegetation-type. Fourwing saltbush is a highly desirable desert-shrub browse species for the reasons given by Dayton (1931, p. 28): "Its importance is due to its abundance, accessibility, size, agreeable saline taste, evergreen habit, high percentage of useableness — leaves, stems, flowers, and fruits all being edible — and tremendous root development enabling great tolerance of drought, ability to withstand low temperature, copious production of fattening, highly palatable seed, and high nutritiousness." Apparently cattle and sheep are more apt to preferentially browse on fourwing saltbush than either horses, deer, or rabbits (Elmore, 1976). These features, plus characteristics that enable the shrub to germinate, establish itself as a seedling, and grow on rather unfavorable raw spoil (Aldon and Springfield, 1973), have made it a highly desirable species for use in land rehabilitation.

BROOM SNAKEWEED

Another common name for this desert half-shrub is "turpentine weed" — an apt description, because this member of the Composite Family emits a very pungent, resinous odor. Broom snakeweed is usually found in well-drained loamy soils, and if abundant is considered an indication of intensive overgrazing. This is because the plant itself is avoided and has no forage value but proliferates at the expense of the loss of the more palatable species. It has little value as a rehabilitation species; however, snakeweed will colonize rehabilitated areas. Therefore, it was sampled throughout the basin (Study 1) and on the Sheppard, Shiprock, and Doak soil series (Study 2) because of its widespread occurrence and its potential importance as an interloper.

REGIONAL BIOGEOCHEMICAL PATTERNS

Table 2 gives the summary statistics for the 35 elements (and ash yield) in three plant species collected. Differences in the GM and observed range for each plant indicate variability in the uptake of a number of elements. For example, the following general observations are made: elements highest in galleta are aluminum, arsenic, cobalt, iron, manganese, mercury, titanium, vanadium, ytterbium, and yttrium; elements lowest in galleta are boron cadmium, calcium, copper, magnesium, potassium, scandium, selenium, strontium, and sulfur. Elements highest in snakeweed are copper, lead, lithium, and sodium; elements (and ash) lowest in snakeweed are ash, chromium, and nickel; elements (and ash) highest in fourwing saltbush are ash, boron, nickel, phosphorus, potassium, selenium, strontium, and zinc; elements lowest in fourwing saltbush are aluminum, arsenic, barium, cobalt, iron, lead, mercury, titanium, uranium, vanadium, ytterbium, yttrium, and zirocnium. Most of these differen-

TABLE 2. — *Summary statistics for the element content of dry material of galleta, broom snakeweed, and fourwing saltbush from the San Juan Basin (Study 1)*

[G, galleta; S, broom snakeweed; F, fourwing saltbush; ppm, parts per million; <, less than; >, more than; leaders (--), mean no data; ratio is the proportion of the number of analyses having values above the lower limit of determination to the total number of analyses]

Element or ash	Material	Ratio	Geometric mean	Geometric deviation	Observed range
Ash (percent)-----	G	25:25	6.8	1.24	4.0 - 10
	S	18:18	5.9	1.22	4.3 - 9.1
	F	10:10	12	1.22	8.4 - 16
Aluminum (percent)	G	25:25	.097	1.75	.025 - .26
	S	18:18	.083	1.76	.023 - .19
	F	10:10	.053	1.49	.030 - .098
Arsenic (ppm)-----	G	25:25	.16	1.43	.10 - .30
	S	18:18	.13	1.53	.050 - .20
	F	6:10	[1].011	[1]1.19	<.050 - .10
Barium (ppm)------	G	25:25	20	1.57	8.6 - 48
	S	18:18	44	1.93	8.8 - 98
	F	10:10	18	1.44	10 - 30
Boron (ppm)-------	G	25:25	5.1	1.61	1.4 - 24
	S	13:18	[1]24	[1]1.48	12 - >36
	F	9:10	[1]27	[1]1.46	17 - >70
Cadmium (ppm)-----	G	24:25	[1].064	[1]1.78	<.025 - .26
	S	18:18	.23	1.65	.10 - .73
	F	10:10	.11	1.27	.048 - .32
Calcium (percent)-	G	25:25	.35	1.34	.23 - .65
	S	18:18	1.0	1.40	.56 - 1.7
	F	10:10	1.4	1.30	1.0 - 2.7
Manganese (ppm)---	G	25:25	85	1.76	22 - 200
	S	18:18	50	1.29	28 - 83
	F	10:10	71	1.60	29 - 160
Mercury (ppm)-----	G	25:25	.25	1.44	.15 - .50
	S	18:18	.19	1.51	.10 - .45
	F	10:10	.11	1.61	.050 - .20
Chromium (ppm)----	G	25:25	1.0	1.38	.56 - 1.8
	S	18:18	.85	1.32	.47 - 1.5
	F	10:10	1.1	1.32	.81 - 1.9
Cobalt (ppm)------	G	25:25	.26	1.57	.072 - .52
	S	18:18	.18	1.86	.051 - .35
	F	9:10	[1].14	[1]1.44	<.085 - .25
Copper (ppm)------	G	25:25	2.4	1.24	1.6 - 4.0
	S	18:18	8.1	1.42	4.6 - 17
	F	10:10	4.7	1.28	3.3 - 7.0
Europium (ppm)----	G	14:25	[1].17	[1]1.86	<.080 - .46
	S	9:18	[1].13	[1]2.35	<.086 - .40
	F	4:10	[1].24	[1]1.81	<.17 - .61
Fluorine (ppm)----	G	25:25	8.5	1.33	4.0 - 14
	S	18:18	9.4	1.36	6.0 - 14
	F	10:10	6.2	1.71	3.0 - 15
Iron (ppm)--------	G	25:25	530	1.49	220 - 1,200
	S	18:18	420	1.60	190 - 820
	F	10:10	220	1.73	87 - 430
Lanthanum (ppm)---	G	20:25	[1]1.3	[1]1.98	<.59 - 3.8
	S	15:18	[1]1.1	[1]1.91	<.47 - 2.4
	F	5:10	[1]1.2	[1]2.79	<1.0 - 4.8
Lead (ppm)--------	G	[2]24:24	.80	1.45	.40 - 2.0
	S	18:18	1.1	1.59	.58 - 3.0
	F	6:10	[1].52	[1]1.37	<.41 - .78
Lithium (ppm)-----	G	21:25	[1].36	[1]1.42	<.22 - .77
	S	18:18	.63	1.73	.26 - 1.4
	F	5:10	[1].45	[1]1.58	<.42 - .92
Magnesium (percent)	G	25:25	.063	1.57	.027 - .14
	S	18:18	.14	1.40	.067 - .36
	F	10:10	.58	1.31	.36 - .78
Molybdenum (ppm)--	G	[3]21:21	.51	1.50	.25 - 1.2
	S	18:18	.54	1.27	.38 - .99
	F	10:10	.49	1.64	.24 - 1.5

TABLE 2. — Continued

Element or ash	Material	Ratio	Geometric mean	Geometric deviation	Observed range
Nickel (ppm)------	G	25:25	.83	1.33	.50 - 1.8
	S	18:18	.66	1.38	.39 - 1.4
	F	10:10	1.2	1.81	.50 - 3.4
Niobium (ppm)-----	G	22:25	[1].70	[1]2.01	<.24 - 2.0
	S	14:18	[1].41	[1]1.96	<.22 - 1.2
	F	4:10	[1].41	[1]3.23	<.36 - 2.2
Phosphorns (percent)	G	25:25	.056	1.52	.016 - .13
	S	18:18	.062	1.33	.042 - .10
	F	10:10	.091	1.53	.059 - .17
Potassium (percent)	G	25:25	.36	1.84	.096 - 1.1
	S	18:18	.74	1.48	.37 - 2.0
	F	10:10	3.0	1.56	1.0 - 4.6
Scandium (ppm)----	G	22:25	[1].25	[1]1.43	<.13 - .51
	S	18:18	.26	1.41	.13 - .61
	F	8:10	[1].30	[1]1.55	<.19 - .59
Selenium (ppm)----	G	25:25	.12	1.62	.060 - .45
	S	18:18	.27	1.84	.080 - 1.2
	F	10:10	.81	3.07	.15 - 4.5
Sodium (ppm)------	G	25:25	77	1.64	35 - 180
	S	18:18	110	1.19	84 - 150
	F	10:10	72	1.48	26 - 100
Strontium (ppm)---	G	25:25	24	1.29	17 - 43
	S	18:18	74	1.57	40 - 150
	F	10:10	87	1.70	48 - 240
Sulfur (total)---- (percent)	G	25:25	.099	1.38	.055 - .22
	S	18:18	.11	1.41	.055 - .24
	F	10:10	.30	1.39	.15 - .54
Titanium (ppm)----	G	25:25	46	2.01	8.6 - 170
	S	18:18	31	2.06	5.5 - 75
	F	10:10	10	2.06	3.5 - 29
Uranium (ppm)-----	G	[4]20:20	.075	1.32	.040 - .12
	S	17:18	[1].11	[1]1.66	<.029 - .21
	F	4:10	[1].044	[1]1.36	<.034 - .072
Vanadium (ppm)----	G	25:25	1.3	1.47	.63 - 2.7
	S	18:18	1.1	1.63	.49 - 2.1
	F	10:10	.70	1.50	.40 - 1.2
Ytterbium (ppm)---	G	19:25	[1].083	[1]1.61	<.056 - .29
	S	14:18	[1].068	[1]1.39	<.047 - .13
	F	0:10	--	--	<.080 - <.13
Yttrium (ppm)-----	G	25:25	.83	1.80	.19 - 3.7
	S	18:18	.68	1.61	.26 - 1.4
	F	7:10	[1].32	[1]1.87	<.22 - .72
Zinc (ppm)--------	G	25:25	13	1.44	8.4 - 37
	S	18:18	17	1.34	9.6 - 27
	F	10:10	19	2.37	6.8 - 77
Zirconium (ppm)---	G	25:25	7.5	2.15	1.5 - 20
	S	18:18	5.2	2.10	1.2 - 23
	F	9:10	[1]1.7	[1]2.06	<.52 - 3.4

---

[1] The technique of Cohen (1959) was used to calculate the mean and deviation because there were one or more concentration values outside of the limits of determination of the analytical method used.

[2] Due to contamination, one sample was eliminated from the calculation of the summary statistics--see Study 1 results section on "Regional biogeochemical patterns".

[3] Four of the original 25 samples were eliminated from the calculation of the summary statistics because they possessed unusually high molybdenum concentrations--see Study 1 results section on "Regional biogeochemical patterns".

[4] Five of the original 25 samples were eliminated from the calculation of the summary statistics because they possessed unusually high uranium concentrations--see Study 1 results section on "Regional biogeochemical patterns".

ces are subtle (less than a factor of two), and may not be significant; however a few are large. For example, ash yield of saltbush is two times that of the other plants; boron in snakeweed and saltbush is four times greater than in galleta; iron in galleta is two times the levels found in saltbush; lead is much higher in galleta and snakeweed when compared to saltbush; the major essential elements calcium, magnesium, potassium, phosporus, and sulfur are generally highest in saltbush; and, selenium content of saltbush is four times greater than the levels in galleta or snakeweed.

The distribution of galleta samples in the San Juan Basin study area enabled us to define some very general regional patterns. Such patterns cannot be defined for snakeweed or fourwing saltbush because only 18 and 10 samples of each, respectively, were collected. The regional patterns for galleta are based on observed differences in concentrations at different sampling sites: the significance of the differences was not tested by AoV because too few of the 48 sites in Study 1 contained galleta (fig. 3). Of the elements examined in galleta, four (manganese, molybdenum, nickel, and uranium) have discernible trends (fig. 8*A*-8*D*), and two others (iron and selenium) show possible trends (fig. 8*E* and 8*F*).

The frequency distributions of these six elements were separated into two or three groups, each representing approximately equal proportions of the total number of samples. For example, the manganese data (fig. 8*A*) is displayed using three classes, each accounting for approximately one-third of the total number of samples.

These figures show that the concentration of manganese, nickel, and probably iron are highest in the south-central part of that portion of the San Juan Basin examined. Selenium in galleta showed a similar pattern except that two samples west of Farmington were also high. The molybdenum and uranium data are unique because the samples can be separated into two populations. The frequency distribution in figure 8*B* shows that 21 of 25 samples of galleta had molybdenum concentrations between 0.23 and 1.1 ppm (parts per million). The other four samples, all from the far western edge of the study area, had unusually high concentrations of between 4.5 and 64 ppm. (Reanalysis of these samples confirmed the high values.) Figure 8*D* shows that 20 of 25 samples of galleta have uranium concentrations ranging from 0.04 to 0.12 ppm, and the remaining samples have slightly higher concentrations of from 0.16 to 0.19 ppm. Four of these samples high in uranium were collected west and southwest of Farmington.

A comparison of the plant-element data to our maps of regional soil-element trands (Severson and Gough, 1981) shows poor correspondence. However, the western side of the study area was very high in total A-horizon molybdenum — this is the area of our highest recorded concentrations of molybdenum in galleta. The pH of the soil at these high-molybdenum sites, however, was not unusually high, suggesting that available molybdenum might not be any greater than at other sites. The concentration of all other elements in galleta from these high-molybdenum sites was also not unusual. We conclude that, under certain as-yet-undefined conditions, molybdenum concentrations in galleta probably reflect total soil molybdenum, and that galleta is capable of concentrating molybdenum in its tissues to levels far above those found in fourwing saltbush, snakeweed, and probably alkali sacaton (see also the molybdenum discussion in the section on "Element toxicity and deficiency considerations").

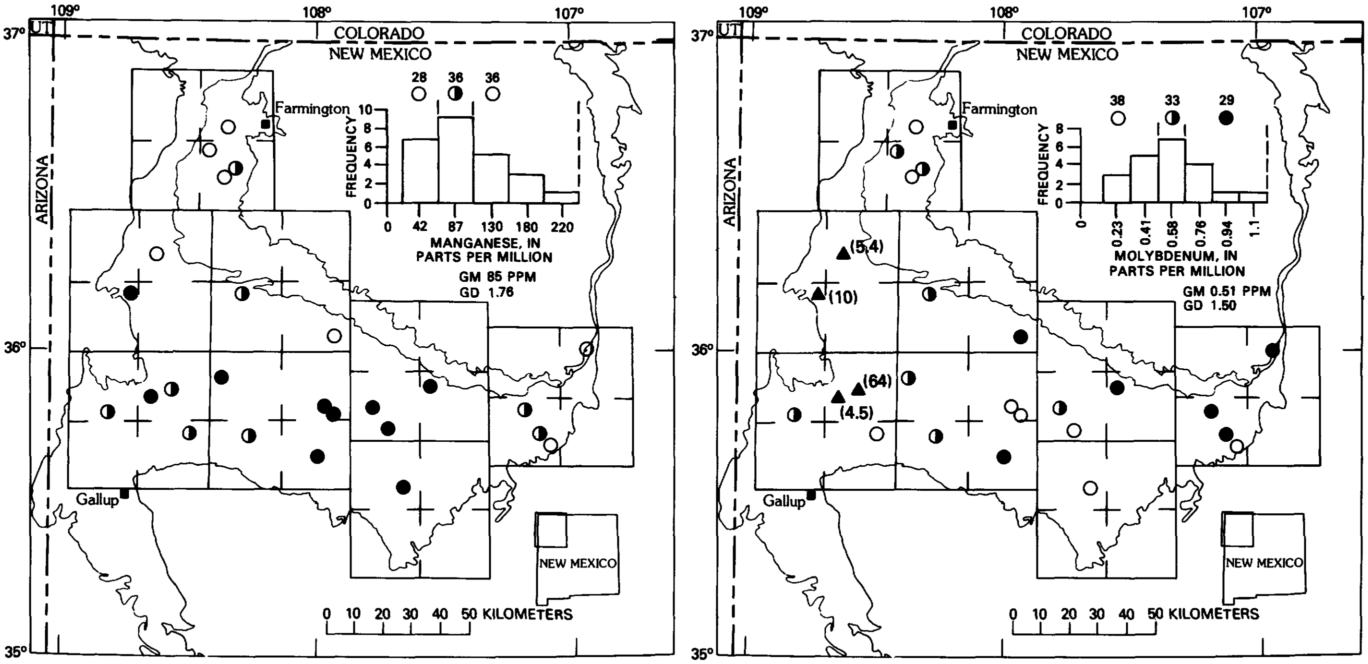
Product-moment correlation coefficients were determined for the log concentration of elements in galleta and broom snakeweed samples, each collected at the same 15 sites (fig. 3) throughout the basin. All samples were considered independent because each site was originally selected at random. Only four elements showed significant correlations: boron, $r = 0.593$; molybdenum, $r = 0.624$; selenium, $r = 0.842$; and zinc, $r = 0.562$. We may assume that the uptake mechanisms for these four elements are probably very similar for galleta and snakeweed. Regional patterns in the element content of snakeweed throughout the basin were not apparent. Lack of regional patterns was also true for molybdenum and selenium, even though these elements showed patterns in galleta, and their concentrations in the two species were significantly correlated.

STUDY 2, ELEMENT CONTENT OF PLANTS GROWING ON THE SHEPPARD, SHIPROCK, AND DOAK SOIL SERIES

STUDY OVERVIEW

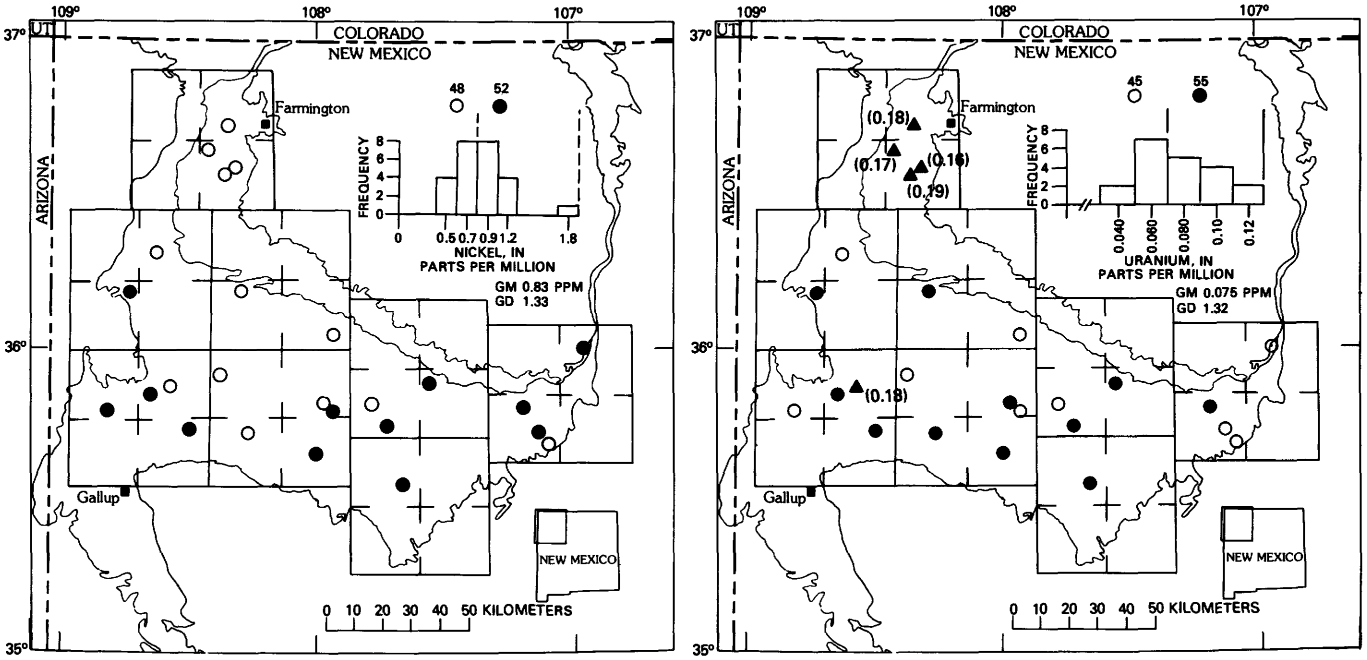
This study concentrated on the area underlain by the Kirtland Shale and Fruitland Formation. The coals in these geologic units have the greatest potential for recovery using surface-mining methods. The native soils of this region vary as to their quality as media for plant growth. The Sheppard, Shiprock, and Doak soil series is a soil group that could be retrieved from the area to be mined and stockpiled for future replacement.

We sampled galleta and broom snakeweed, as well as A- and C-horizons of the Sheppard, Shiprock, and Doak soil series, using the procedure detailed in the "Methods" section for Study 2. The samples were collected at random points defined by a barbell cluster. Three barbell clusters were positioned at random points within the study area (fig. 4). The purpose of the study was to estimate at what distance increment most



A. Manganese (dry-weight basis) in galleta

B. Molybdenum (dry-weight basis) in galleta



C. Nickel (dry-weight basis) in galleta

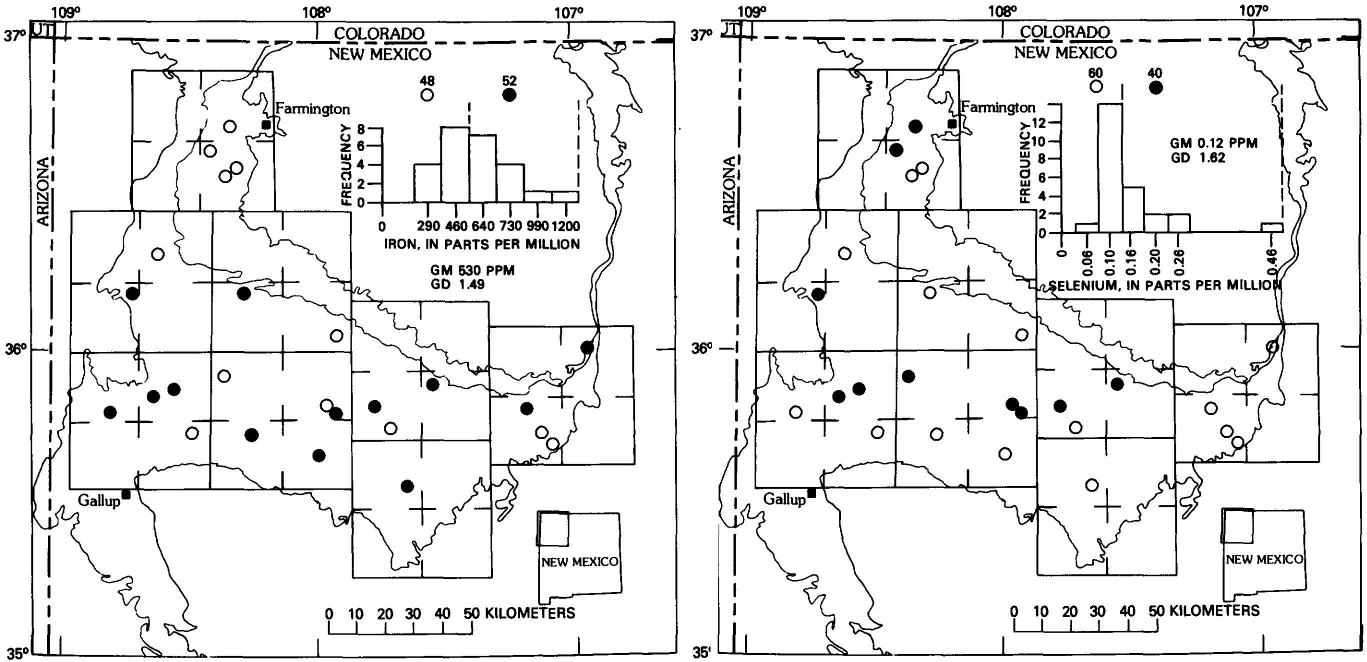
D. Uranium (dry-weight basis) in galleta

FIGURE 8 (above and facing page). — Concentrations of manganese, molybdenum, nickel, uranium, iron, and selenium in galleta grass at 25 sampling locations from Study 1, expressed by symbols as concentration classes and by the geometric mean (GM) and geometric deviation (GD). The numbers above the frequency diagram are the percentages of the samples in each class. The class boundaries are indicated by vertical dashed lines. The sites marked with triangles (molybdenum and uranium) possessed concentrations (noted in parentheses) considered outside the normal range.

of the areal variability in the element content of a plant species occurred. This information was used to determine whether or not regional element patterns in plants were present, and to calculate biogeochemical baselines where appropriate.

GEOGRAPHICAL DISTANCE-RELATED ELEMENT VARIABILITY AND BASELINES

Samples of galleta grass were collected at all 30 randomly selected sites and broom snakeweed at 27 of



E. Iron (dry-weight basis) in galleta

F. Selenium (dry-weight basis) in galleta

FIGURE 8. — Continued

30 sites. The absence of three samples of snakeweed from the unbalanced AoV design made the total number of samples for each barbell unequal (table 3). The F test for estimating significant differences between the barbells was not materially affected because the absence of the three samples did not appreciably change the coefficients used to estimate the mean square. Also, nine of the 35 elements analyzed required the replacement of censored values prior to the analysis of variance. Table 3 lists these elements and gives the replacement ratio for each of the three barbells and for each of the two plant species. For reference purposes the barbell locations have been numbered from north to south (fig. 4).

Tables 4 and 5 give the results of the analysis of variance for element concentrations in galleta and snakeweed and the summary statistics (GM, GD, observed range, and the expected 95-percent range) for each element. The expected 95-percent range is the "baseline" as first proposed by Tidball and Ebens (1976) and is calculated as a concentration range bracketed by the GM/GD^2 to the GM·GD^2. Tidball and Ebens (1976, p. 300) explained that the "*** 95-percent expected range is broader than a 95-percent confidence interval *** [it] is broader because it accounts for the variability among *individual* samples as measured by the standard deviation; the confidence interval reflects the indeterminacy in the *mean* of the distribution and is measured by the standard error of the mean."

The proportion of the total $\log_{10}$ variance that is explained by each of the five distance increments, plus the proportion of the variability explained as analytical error, are given for 35 elements plus ash yield (tables 4 and 5). The three distance increments of most interest are greater than 10 km (regional component or variability between barbell clusters), less than 0.1 km (local component or variability at a distance of less than 100 m), and the component associated with variability due to analytical error (precision). When the analytical error exceeded 50 percent of the total vari-

TABLE 3. — *Detection ratios for elements in the ash of galleta and broom snakeweed (Study 2)*

[Ratios are the number of values above the lower limit of determination to the number of samples analyzed; ratios are based on each of the three barbell units (fig. 4)]

Element	Galleta Barbell 1	 Barbell 2	 Barbell 3	Broom snakewead Barbell 1	 Barbell 2	 Barbell 3
Boron[1]	10:10	10:10	10:10	8:8	9:10	9:9
Europium	6:10	7:10	7:10	6:8	10:10	5:9
Lanthanum	9:10	10:10	2:10	8:8	10:10	7:9
Lithium	9:10	10:10	3:10	8:8	10:10	9:9
Molybdenum	10:10	10:10	9:10	8:8	10:10	9:9
Niobium	9:10	8:10	7:10	6:8	8:10	8:9
Scandium	10:10	10:10	9:10	8:8	10:10	9:9
Uranium	9:10	10:10	10:10	8:8	10:10	9:9
Ytterbium	9:10	10:10	6:10	8:8	8:10	4:9

[1] Ratios for the number of values below the upper limit of determination to the number of samples analyzed.

TABLE 4.— *Variation in and summary statistics for the element concentrations in dry material of galleta growing in the Shepard, Shiprock and Doak soil association, San Juan County (Study 2)*

[Except as noted, the geometric deviation was calculated from the total variance; *, component of variance was tested as significant at the 0.05 probability level for the specified geographic distance increment; ratio, the proportion of the number of analyses having values above the lower limit of determination to the total number of analyses. >, greater than; <, less than; ppm, parts per million]

		Analysis of variance							Summary statistics			
			Percentage of total variance between									
Element or ash	Ratio	Total $\log_{10}$ variance	Barbells, > 10 km distance	5-10 km distance	1-5 km distance	0.1-1 km distance	<0.1 km distance	Analyses	Geometric mean (ppm)	Geometric deviation	Observed range (ppm)	Expected 95 percent range (baseline, ppm)[1]
Ash-----------	30:30	0.0088	<1	28	<1	15	22	35	7.4	1.24	5 - 11	4.8 - 11
Aluminum------	30:30	.0708	*67	3	3	5	7	16	1,800	1.85	490 - 4,700	530 - 6,200
Arsenic-------	30:30	.0286	11	*39	<1	5	23	23	.15	1.48	.050 - .25	.070- .32
Barium--------	30:30	.0441	29	11	<1	3	*41	16	25	1.62	9.2 - 57	9.7 - 64
Boron---------	30:30	.0432	<1	*70	7	<1	<1	23	5.0	1.61	3.2 - 16	2.0 - 13
Cadmium-------	30:30	.1224	<1	16	<1	33	29	22	.092	2.24	.037 - .45	.019- .45
Calcium-------	30:30	.0282	<1	*71	<1	8	*17	5	3,500	1.47	2,100 - 7,900	1,600 - 7,400
Chromium------	30:30	.0363	<1	8	<1	15	<1	76	1.3	1.55	.69 - 2.4	-- - --
Cobalt--------	30:30	.0634	47	6	4	15	11	17	.27	1.79	.072 - .55	.086- .84
Copper--------	30:30	.0254	<1	36	10	<1	*38	16	2.9	1.44	1.6 - 7.3	1.4 - 5.9
Europium------	20:30	.0686	<1	6	<1	<1	24	69	[2].19	[2]1.71	<.12 - .42	-- - --
Fluorine------	30:30	.0204	36	*21	<1	<1	13	30	6	1.39	3.0 - 10	3.1 - 11
Iron----------	30:30	.0519	*69	4	2	5	9	11	730	1.69	220 - 1,600	260 - 2,100
Lanthanum-----	20:30	.1454	34	12	7	<1	2	45	[2]1.1	[2]2.40	<.46 - 4.4	.20 - 6.2
Lead----------	30:30	.0243	24	30	10	<1	<1	36	1.2	1.43	.61 - 2.2	.60 - 2.4
Lithium-------	22:30	.0388	29	8	<1	13	<1	51	[2].34	[2]1.37	<.20 - .60	-- - --
Magnesium-----	30:30	.0271	14	*47	18	<1	*14	7	730	1.46	430 - 1,800	350 - 1,500
Manganese-----	30:30	.0193	31	19	9	4	*25	12	93	1.38	54 - 200	49 - 170
Mercury-------	30:30	.0570	13	15	10	<1	*54	8	.24	1.73	.070 - .70	.082- .70
Molybdenum----	29:30	.0466	<1	14	40	16	*21	8	[2].34	[2]1.53	<.14 - .82	.13 - .90
Nickel--------	30:30	.0273	<1	33	24	4	*30	8	.90	1.46	.46 - 1.7	.43 - 1.9
Niobium-------	24:30	.1162	2	<1	23	<1	16	63	[2].67	[2]2.02	<.24 - 1.9	-- - --
Phosphorus----	30:30	.0140	27	<1	41	8	14	10	510	1.30	320 -- 990	300 - 860
Potassium-----	30:30	.0455	4	*52	*27	<1	*11	6	3,100	1.63	1,700 -12,000	1,200 - 8,100
Scandium------	29:30	.0337	48	11	<1	6	9	26	[2].26	[2]1.46	<.13 - .57	.11 - .60
Selenium------	30:30	.0335	4	35	<1	*48	*12	1	.081	1.52	.040 - .25	.036- .18
Sodium--------	30:30	.0307	13	<1	*50	2	20	15	61	1.50	37 - 150	28 - 130
Strontium-----	30:30	.0180	<1	24	<1	13	13	49	22	1.36	10 - 43	12 - 40
Sulfur (total)	30:30	.0948	*65	7	<1	11	<1	17	1,200	1.87	280 - 2,800	340 - 4,200
Titanium------	30:30	.0334	<1	35	3	*33	<1	29	72	1.47	37 - 160	33 - 160
Uranium-------	29:30	.1081	<1	*36	*11	<1	*45	8	[2].081	[2]1.75	<.035 - .27	.018- .36
Vandium-------	30:30	.0569	*66	5	<1	7	11	12	1.2	1.73	.47 - 3.1	0.40 - 3.6
Ytterbium-----	25:30	.0381	40	5	<1	<1	*37	18	[2].092	[2]1.48	<.050 - .24	.038- .22
Ytterium------	30:30	.0640	48	15	1	<1	20	16	.84	1.79	.22 - 2.2	.27 - 2.6
Zinc----------	30:30	.0307	16	14	<1	15	*34	20	12	1.50	5 - 26	5.4 - 26
Zirconium-----	30:30	.1402	*41	<1	<1	<1	32	27	8.1	2.37	1.7 - 36	1.4 - 46

[1] Because of a significant regional variance component (>10 km), the summary statistics for aluminum, iron, sulfur, vanadium, and zirconium are biased if applied to specific areas of the soil association; they are unbiased if applied countywide. Because of excessive analytical error (>50 percent), baselinas for chromium, europium, lithium, and niobium were not calculated.

[2] The technique of Cohen (1959) was used to calculate the mean and deviation because one or more concentration values were outside of the limits of determination of the analytical method used.

ability for an element, a baseline (expected 95 percent range) was not calculated. A baseline based on excessive analytical error measures predominantly imprecision and not the natural variability in the data.

Tables 4 and 5 show that 14 percent of the elements in galleta, and none in snakeweed, have a significant (p less than 0.05) regional-variance component. This variation means that the concentrations of aluminum, iron, sulfur, vandium, and zirconium, in galleta differ significantly when sampled at sites more than 10 km apart. Further, greater than 65 percent of the total variability for all of these elements, except zirconium, was measured at this distance increment. Of these elements, only the total zirconium amounts in A- and C-horizon soils also showed a significant regional component (Severson and Gough, 1981); however, in the soils less than 33 percent of the total variability in the zirconium data was explained. Although the summary statistics, including the 95 percent expected range, are given for these five elements, it should be realized that, because of the significant regional variance component, these data are biased if compared to

TABLE 5.— *Variation in and summary statistics for the element concentrations in dry material of broom snakeweed growing in the Sheppard, Shiprock and Doak soil association, San Juan County (Study 2)*

[Except as noted, the geometric deviation was calculated from the total variance; *, component of variance was tested as significant at the 0.05 probability level for the specified geographic distance increment; ratio, the proportion of the number of analyses having values above the lower limit of determination to the total number of analyses. >, greater than; <, less than; ppm, parts per million]

Element or ash	Ratio	Analysis of variance							Summary statistics			
		Total log$_{10}$ variance	Percentage of total variance between									
			Barbells, > 10 km distance	5-10 km distance	1-5 km distance	0.1-1 km distance	<0.1 km distance	Analyses	Geometric mean (ppm)	Geometric deviation	Observed range (ppm)	Expected 95 percent range (baseline, ppm)[1]
Ash-----------	27:27	0.0126	11	29	17	16	*24	4	7.0	1.29	3.8 - 9.5	4.2 - 11
Aluminum------	27:27	.0435	<1	27	32	*26	5	11	1,600	1.62	710 - 3,300	620 - 4,100
Arsenic-------	27:27	.0536	<1	17	31	28	*16	7	.18	1.70	.050 - .45	.064- .51
Barium--------	27:27	.0360	<1	21	<1	65	<1	14	50	1.55	25 - 85	21 - 120
Boron---------	26:27	.0210	<1	27	23	2	<1	48	[2]21	[2]1.34	11 - >42	11 - 41
Cadmium-------	27:27	.0309	<1	28	26	8	*28	10	.23	1.50	.084 - .45	.10 - .51
Calcium-------	27:27	.0387	15	<1	<1	*71	*11	3	12,000	1.57	6,100 -23,000	5,000 -29,000
Chromium------	27:27	.0391	<1	<1	*56	<1	12	32	1.4	1.58	.67 - 2.8	.57 -- 3.4
Cobalt--------	27:27	.0851	<1	13	40	32	<1	15	.27	1.96	.084 - .67	.072- 1.0
Copper--------	27:27	.0268	<1	4	<1	*34	<1	62	9.9	1.46	6.6 - 15	-- - --
Europium------	21:27	.0529	<1	13	1	<1	25	61	[2].22	[2]1.55	<.084 - .51	-- - --
Fluorine------	27:27	.0160	24	3	19	2	*44	8	9.4	1.34	4.0 - 14	5.3 - 17
Iron----------	27:27	.0360	<1	17	30	*32	*15	6	640	1.55	280 - 1,200	270 - 1,500
Lanthanum-----	25:27	.0884	5	<1	54	14	12	14	[2]1.4	[2]1.77	<.55 - 3.8	.37 - 5.3
Lead----------	27:27	.0363	27	4	<1	9	*48	12	1.6	1.55	.64 - 2.9	.68 - 3.8
Lithium-------	27:27	.0370	<1	28	<1	33	34	5	.81	1.56	.42 - 2.2	.34 - 1.9
Magnesium-----	27:27	.0221	21	*64	<1	5	7	4	1,300	1.41	760 - 2,200	660 - 2,500
Manganese-----	27:27	.0173	9	26	*33	<1	17	15	70	1.35	42 - 120	39 - 130
Mercury-------	27:27	.0175	<1	<1	10	26	22	42	.19	1.36	.10 - .30	.10 - .35
Molybdenum----	27:27	.0400	11	<1	<1	*61	16	13	.35	1.58	.14 - .67	.14 - .86
Nickel--------	27:27	.0382	<1	<1	*83	6	6	5	.69	1.57	.38 - 2.7	.28 - 1.7
Niobium-------	22:27	.0965	27	2	8	<1	<1	63	[2].52	[2]1.74	<.18 - 1.6	-- - --
Phosphorus----	27:27	.0177	30	*50	2	<1	*16	2	610	1.36	340 -- 920	330 - 1,100
Potassium-----	27:27	.0429	38	*31	<1	11	*18	1	7,800	1.61	3,800 -14,000	3,100 -20,000
Scandium------	27:27	.0195	<1	<1	58	8	10	24	.26	1.38	.14 - .38	.14 - .49
Selenium------	27:27	.0358	36	9	<1	14	*33	8	.25	1.55	.10 - .45	.10 - .59
Sodium--------	27:27	.1022	7	<1	<1	*78	*13	1	100	2.09	41 - 590	24 - 420
Strontium-----	27:27	.0429	<1	<1	<1	*79	*17	3	56	1.61	23 - 97	22 - 140
Sulfur (total)	27:27	.0506	<1	2	3	*68	*19	7	1,000	1.66	400 - 2,400	360 - 2,800
Titanium------	27:27	.0378	9	*54	12	<1	*16	8	92	1.52	38 - 160	40 - 210
Uranium-------	27:27	.0336	30	<1	16	*29	4	20	.098	1.52	.049 - .19	.043- .22
Vanadium-------	27:27	.0386	<1	26	13	*46	8	7	1.2	1.57	.59 - 2.4	.84 - 1.7
Ytterbium-----	20:27	.0448	<1	53	7	*29	5	6	[2].074	[2]1.42	<.037 - .14	.028- .19
Yttrium------	27:27	.0412	<1	20	41	*27	<1	11	.74	1.60	.35 - 1.4	.29 - 1.8
Zinc----------	27:27	.0221	4	4	<1	*68	*21	4	18	1.41	12 - 35	9.2 - 35
Zirconium-----	27:27	.0972	<1	43	9	23	<1	24	5.3	2.05	2.2 - 14	1.3 - 22

[1] Because of excessive analytical error (>50 percent), baselines for copper, europium, and niobium were not calculated.

[2] The technique of Cohen (1959) was used to calculate the mean and deviation because one or more concentration values were outside of the limits of determination of the analytical method used.

a newly collected sample from a specific area of Study 2. They are unbiased, however, if the baseline is used to characterize typical concentrations from the entire Study 2 area. Although none of the elements in snakeweed possessed a significant regional component, variability at the 5-10-km increment was significant for potassium, magnesium, phosphorus, and titanium.

Most of the variability in the element data was associated with the local component (less than 0.1 km). Thirty-six percent of the elements in galleta and 44 percent in snakeweed showed significant local variance. This significant variance means that samples of galleta and snakeweed more than 10 km apart vary in their content of these elements little more than plants sampled as close together as 0.1 km. For most elements, therefore, the uniformity in the content of these two plant species indicates that only a few samples are needed to characterize a rather large area. The gross availability of these elements in the Sheppard, Shiprock, and Doak soil series is assumed, therefore, to be similar throughout the Study 2 area.

The AoV described above was designed to assess the variability in the element data of the plants at six distance-related increments. An assessment of only the difference between barbell clusters, as calculated by a multiple-mean comparison test (Natrella, 1966), is given in table 6. Many elements in galleta showed significant differences in the element means between barbells. Fourteen of the elements (aluminum, arsenic, barium, cobalt, fluorine, iron, lead, manganese, scandium, sulfur, vanadium, ytterbium, yttrium, and zirconium) were highest in their concentrations at barbells 1 and 2 and lowest at barbell 3 (table 6). Other elements (nickel, niobium, and strontium) and ash showed differences between barbells 1 and 3 but not between barbells 2 and 3. Again, the southeastern most barbell (barbell 3) was lowest in the average concentration of these three elements. For most elements in snakeweed, no difference between the barbell means was found, and, therefore, no trends (as for galleta) are apparent.

TABLE 6.— *Multiple-mean comparison of barbell units of the average element concentrations in galleta and broom snakeweed (Study 2)*

[GM, geometric mean concentration of elements (and ash yield) in dry plant material; values preceeded by alpha superscript are not significantly different at the 0.05 probability level; all measurements are in parts per million unless otherwise noted; n, number of samples]

Element or ash	Galleta			Broom snakeweed		
	GM, barball 1 (n=10)	GM, barbell 2 (n=10)	GM, barbell 3 (n=10)	GM, barball 1 (n=8)	GM, barball 2 (n=10)	GM, barball 3 (n=9)
Ash[1]	^{a}8.1	^{ab}7.4	^{b}6.8	^{b}6.4	^{b}6.7	^{a}8.1
Aluminum	^{a}2,600	^{a}2,200	^{b}950	^{a}1,700	^{a}1,500	^{a}1,600
Arsenic	^{a}.17	^{a}.18	^{b}.11	^{a}.21	^{a}.17	^{a}.16
Barium	^{a}32	^{a}29	^{b}16	^{a}58	^{ab}49	^{b}44
Boron	^{b}4.8	^{b}4.3	^{a}6.2	^{b}71	^{a}22	^{a}23
Cadmium	^{a}.10	^{a}.093	^{a}.083	^{ab}.24	^{b}.19	^{a}.27
Calcium	^{a}3,300	^{a}3,400	^{a}3,600	^{b}9,500	^{ab}12,000	^{a}13,000
Chromium	^{a}1.3	^{a}1.3	^{a}1.4	^{a}1.5	^{a}1.3	^{a}1.4
Cobalt	^{a}.34	^{a}.34	^{b}.17	^{a}.33	^{ab}.30	^{b}.21
Copper	^{a}3.0	^{a}2.8	^{a}2.7	^{a}10	^{a}9.5	^{a}10
Europium	^{a}.20	^{a}.20	^{a}.19	^{ab}.12	^{a}.26	^{b}.067
Fluorine	^{a}7.0	^{a}6.5	^{b}4.7	^{a}11	^{a}10	^{b}7.5
Iron	^{a}980	^{a}930	^{b}430	^{a}710	^{a}640	^{a}580
Lanthanum	^{b}1.3	^{a}2.1	^{c}.56	^{a}1.7	^{a}1.6	^{b}.95
Lead	^{a}1.4	^{a}1.2	^{b}.92	^{a}1.6	^{a}2.0	^{b}1.1
Lithium	^{a}.42	^{b}.34	^{c}.21	^{a}.92	^{ab}.85	^{b}.69
Magnesium	^{b}640	^{b}630	^{a}960	^{b}1,200	^{b}1,300	^{a}1,700
Manganese	^{a}120	^{a}110	^{b}72	^{b}58	^{a}74	^{a}76
Marcury	^{a}.29	^{b}.18	^{a}.27	^{a}.20	^{a}.18	^{a}.20
Molybdenum	^{a}.33	^{a}.39	^{a}.30	^{ab}.36	^{a}.42	^{b}.28
Nickel	^{a}1.1	^{ab}.90	^{b}.75	^{a}.62	^{a}.78	^{a}.68
Niobium	^{a}.91	^{ab}.59	^{b}.58	^{b}.36	^{b}.49	^{a}.75
Phosphorus	^{c}430	^{b}510	^{a}600	^{b}500	^{b}570	^{a}770
Potassium	^{b}2,500	^{b}2,700	^{a}4,300	^{b}6,400	^{b}6,500	^{a}12,000
Scandium	^{a}.33	^{a}.30	^{b}.17	^{a}.24	^{a}.27	^{a}.27
Selenium	^{a}.068	^{a}.080	^{a}.10	^{b}.18	^{a}.28	^{a}.29
Sodium	^{a}67	^{b}50	^{a}69	^{a}100	^{a}90	^{a}110
Strontium	^{a}25	^{ab}21	^{b}19	^{a}50	^{a}58	^{a}59
Sulfur (total)	^{a}1,600	^{a}1,800	^{b}590	^{a}1,300	^{a}1,100	^{a}800
Titanium	^{a}65	^{a}67	^{a}85	^{b}79	^{b}80	^{b}120
Uranium	^{a}.10	^{a}.066	^{a}.080	^{b}.087	^{a}.13	^{b}.080
Vandium	^{a}1.7	^{a}1.6	^{b}.72	^{a}1.4	^{a}1.2	^{a}1.1
Ytterbium	^{a}.11	^{a}.11	^{b}.063	^{a}.074	^{a}.075	^{a}.064
Yttrium	^{a}1.1	^{a}1.1	^{b}.50	^{b}.77	^{a}.84	^{b}.62
Zinc	^{a}14	^{b}11	^{ab}13	^{a}16	^{a}19	^{a}18
Zirconium	^{a}12	^{a}12	^{b}3.8	^{a}5.2	^{a}5.3	^{a}5.4

[1] Values are in percent.

STUDY 3, SAN JUAN MINE

Our study at the San Juan mine had the following objectives: (1) to compare the element concentrations in fourwing saltbush growing at a mine rehabilitation site to basin-wide control samples; (2) to assess the partitioning of the distance-related variability in the element concentration of fourwing saltbush and alkali sacaton at a mine rehabilitation site; and (3) to examine soil-plant element uptake relationships at both altered and native sites.

PLANT-ELEMENT CONCENTRATION COMPARISONS

The geometric mean and observed ranges in the concentration of 35 elements in the dry material of basin-wide fourwing saltbush controls and San Juan mine saltbush samples are listed in tables 2 and 7, respectively. These data show that concentrations of aluminum, arsenic, boron, cobalt, copper, fluorine, iron, lead, manganese, sodium, and uranium in samples of fourwing saltbush growing over spoil at the mine generally exceed the concentrations in control samples growing in native soils. The mine samples are commonly two to five times higher in these elements than the control samples. Of particular interest are the concentrations of sodium in saltbush: the mine samples have concentrations that are 100 times higher than the control samples. The relations between mine samples and control samples for these 11 elements are depicted in figure 9. In this figure, element concentrations increase from left to right (along a logarithmic scale) and from the bottom of the figure to the top (from arsenic to aluminum). The GM for the controls is based on 10 samples, whereas the values for the six mine samples are individually plotted (dots). Geometric mean values for arsenic, boron, lead, and uranium were calculated using the technique of Cohen (1959) because of the occurrence of at least one value outside of the limit of analytical determination (table 2). The very narrow range of values for arsenic (GD 1.19) and the occurence of four censored values (table 2) caused the seemingly unusual positioning of the arsenic GM (fig. 9).

In addition to the 11 elements above, concentrations of barium, cadmium, chromium, molybdenum, nickel, zinc, and a few others were slightly higher in mine samples than in control samples based on a comparison of their GM values only. However, a comparison of their observed ranges shows both mine and control samples to be similar. The fact that the GM values for these six elements in the mine samples are higher than the control samples should be noted; however, the following discussion concentrates only on those 11 ele-

TABLE 7.— *Variation in and summary statistics for element concentrations in dry material of fourwing saltbush growing over spoil at the San Juan mine (Study 3)*

[Except as noted, the geometric deviation was calculated from the total variance; *, component of variance was tested as significant at the 0.05 probability level for the specified geographic distane increment; ratio, proportion of the number of analyses having values above the lower limit of determination to the total number of analyses; leaders (--), no data available; ppm, parts per million; <, less than]

Element or ash	Ratio	Analysis of variance: Total $\log_{10}$ variance	Percentage of total variance between: 25-100 m distance	5-25 m distance	<5 m distance plus analytical splits	Summary statistics: Geometric mean (ppm)	Geometric deviation	Observed range (ppm)
Ash----------	6:6	0.0013	<1	60	40	13	1.09	12 - 15
Aluminum------	6:6	.0175	<1	51	49	1,200	1.36	880 - 1,700
Arsenic-------	6:6	.0080	4	<1	96	.24	1.23	.20 - .30
Barium--------	6:6	.0373	<1	50	50	26	1.56	17 - 42
Boron---------	4:6	.0213	27	*72	1	[1]57	[1]1.27	40 - >65
Cadmium-------	6:6	.1469	6	<1	94	.17	2.42	.052 - .26
Calcium-------	6:6	.0121	*43	<1	57	10,000	1.29	9,100 - 14,000
Chromium------	6:6	.0047	56	<1	44	21	1.17	1.8 - 25
Cobalt--------	6:6	.0278	60	16	24	.47	1.47	.28 - .65
Copper--------	6:6	.0041	12	<1	88	9.7	1.16	8.4 - 12
Europium------	3:6	--	--	--	--	[1].29	[1]2.27	<.24 - .74
Fluorine------	6:6	.0177	<1	7	93	20	1.36	15 - 34
Iron----------	6:6	.0108	<1	<1	99	780	1.27	620 - 1,100
Lanthanum-----	2:6	--	--	--	--	[1]1.1	[1]1.51	<1.2 - 1.8
Lead----------	6:6	.0158	<1	<1	99	1.2	1.34	.096 - 1.7
Lithium-------	6:6	.0284	10	<1	90	1.7	1.47	1.1 - 2.5
Magnesium-----	6:6	.0029	<1	64	36	7,200	1.13	610 - 8,400
Manganese-----	6:6	.0410	<1	92	8	160	1.59	90 - 240
Mercury-------	6:6	.0396	<1	<1	99	.13	1.58	.080 - 20
Molybdenum----	6:6	.0389	<1	<1	99	.73	1.57	.53 - 1.3
Nickel--------	6:6	.0442	24	<1	76	1.9	1.62	1.1 - 3.4
Niobium-------	4:6	.2039	57	*42	1	[1]1.0	[1]2.62	<.52 - 3.0
Phosphorus----	6:6	.0108	16	<1	84	840	1.27	650 - 1,200
Potassium-----	6:6	.0090	<1	50	50	26,000	1.24	21,000 - 34,000
Scandium------	6:6	.0070	<1	74	26	.43	1.21	.34 - .51
Selenium------	6:6	.1032	*90	2	8	.22	2.10	.10 - .45
Sodium--------	6:6	.5355	17	<1	83	7,400	5.39	540 - 20,000
Strontium-----	6:6	.0199	73	<1	27	48	1.38	35 - 71
Sulfur (total)	6:6	.0046	<1	<1	99	4,500	1.17	4,000 - 5,200
Titanium------	6:6	.0315	<1	23	77	43	1.50	25 - 64
Uranium-------	6:6	.0107	38	<1	62	.11	1.27	.072 - .13
Vanadium-------	6:6	.0107	<1	41	59	1.9	1.27	1.5 - 2.7
Ytterbium-----	0:6	--	--	--	--	--	--	<.11 - --
Yttrium-------	6:6	.0232	<1	50	50	.81	1.42	.60 - 1.3
Zinc----------	6:6	.0543	<1	*95	5	56	1.71	27 - 86
Zirconium-----	6:6	.0428	<1	12	88	5.1	1.61	3.1 - 8.6

[1] The technique of Cohen (1959) was used to calculate the mean and deviation because there were one or more concentration values outside of the limits of determination.

ments (fig. 9) that showed the greatest differences.

Only selenium was consistently higher in saltbush samples from the basin when compared to samples from the mine. A discussion of this trend follows in the section on "Element toxicity and deficiency considerations." Trends for strontium and the major essential

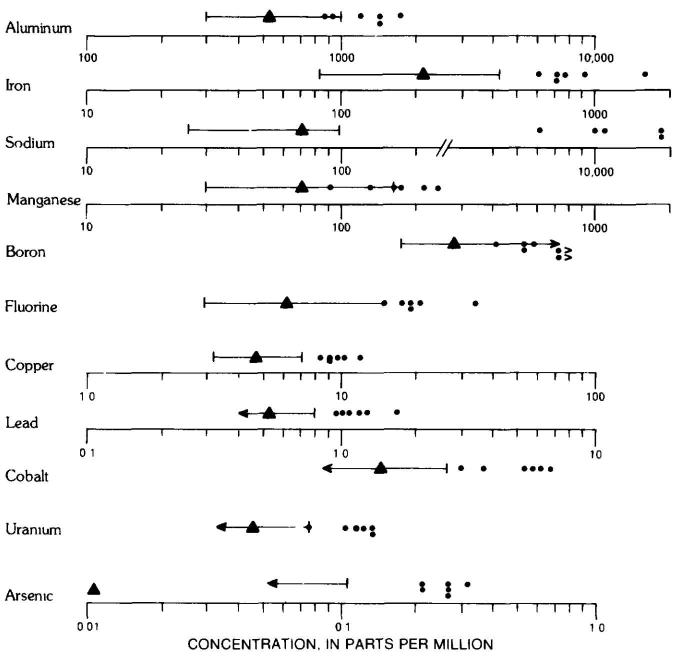


FIGURE 9. — Concentrations of elements (dry-weight basis) in four-wing saltbush at the San Juan mine (dots) that generally exceed values obtained in control samples from the San Juan Basin. Bars represent the observed concentration range in basin-wide samples, and triangles are the geometric mean of the ranges (10 samples). Arrows indicate that either the lower or upper end of the range is indeterminate because at least one value exceeded the lower or upper limit of determination for the analytical methods used. >, greater than.

elements calcium, potassium, and phosphorus, are similar but less pronounced than those for selenium.

Alkali sacaton, a perennial bunchgrass, was sampled only at the mine, so we are unable to compare its summary statistics in table 8 with control samples. Provisional comparisons can be made, however, between sacaton collected at the mine and galleta grass collected throughout the basin (table 2). We recognize that these two grasses are genetically distinct; however, a comparison of the two is reasonable because their ash yields are similar and little difference was noted in their overall element concentrations. Only the concentrations of sodium show large differences between these two species — the mine sacaton samples are 20 times higher in sodium than the basin-wide galleta samples. Other elements, such as sulfur, uranium, and lead, showed slightly elevated levels in mine samples; however, concentrations of manganese, phosphorus, and selenium were slightly less in mine samples.

Comparisons of element concentrations between shrubs and grasses, both on and off altered sites, may be helpful in assessing gross soil-element availability differences. Interspecific inherent differences also govern element uptake and must be considered when assessing the following observations. Mine-sampled sacaton has similar element content to basin-wide saltbush samples but is very much below the concentrations of elements in mine saltbush. Concentrations of mercury, lead, and uranium were the exceptions; these elements showed slightly higher concentrations in mine sacaton than in basin-wide saltbush or mine saltbush. These three elements (plus perhaps molybdenum) were the only elements that were elevated in their concentrations in sacaton tissue over concentrations observed for saltbush. Basin-wide galleta samples showed a similar tendency to accumulate mercury and molybdenum in particular, and lead and uranium to a lesser extent. This tendency may be a unique characteristic of these two grass species and merits additional study. Further discussions of the selective uptake of certain elements by the species sampled are included in the following section.

SOIL-PLANT ELEMENT RELATIONS

A detailed discussion of the extractable and total concentrations of more than 30 elements in native soils and mine soils from northwestern New Mexico is given in Severson and Gough (1981). The purpose of this discussion is to evaluate element concentration levels in soils and mine soils as they may affect plant-element levels.

Figure 9 shows the concentration of 11 elements in saltbush that had elevated levels in San Juan mine samples when compared to basin-wide samples. Assuming that the basin-wide samples are a good measure of background levels of these elements in saltbush, then the higher concentrations observed in the mine samples reflect a greater degree of availability of these elements in the replaced topsoil or spoil or both. Figures 10, 11, and 12 show the GM values for the total concentration of 10 of these 11 elements (concentrations of fluorine were below the detection limit of 400 ppm) in basin-wide A and C horizons of soil and in San Juan mine replaced topsoil and regraded spoil. These figures also give the DTPA-extractable concentrations (ppm in soil) of cobalt, copper, iron, manganese and lead, the water saturation-extractable amounts (meq/L of extract) of sodium, and the hot water-extractable levels (ppm in soil) of boron.

As shown in figure 10, in general, the total concentration of copper, iron, manganese, sodium, aluminum, and uranium were higher in the mine samples than in the basin-wide samples. Extractable levels of copper, iron, manganese, and sodium showed a similar trend (we do not have extractable data for aluminum or uranium). Figure 11 gives trends for cobalt and

TABLE 8.— *Variation in and summary statistics for element concentrations in dry material of alkali sacaton growing over spoil at the San Juan mine (Study 3)*

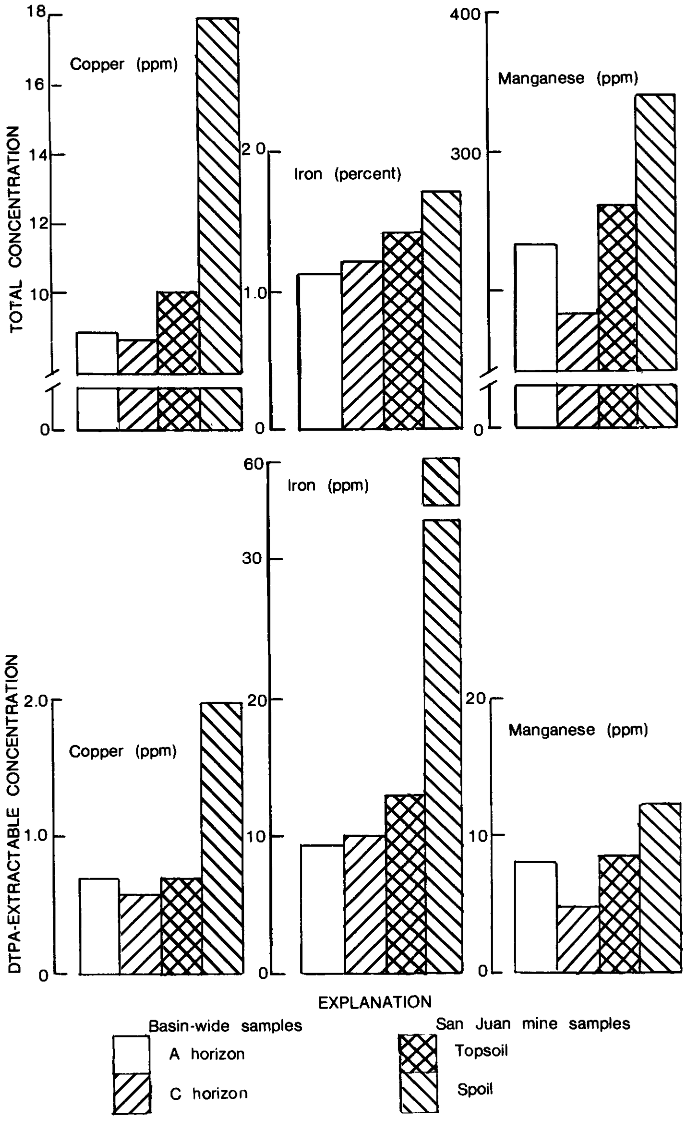
[Except as noted, the geometric deviation was calculated from the total variance; *, component of variance was tested as significant at the 0.05 probability level for the specified geographic distance increment; ratio, proportion of the number of analyses having values above the lower limit of determination to the total number of analyses; leaders (--), no data available; ppm, parts per million; < , less than]

Element or ash	Ratio	Analysis of variance: Total $\log_{10}$ variance	Percentage of total variance between: 25-100 m distance	5-25 m distance	<5 m distance plus analytical splits	Summary statistics: Geometric mean (ppm)	Geometric deviation	Observed range (ppm)
Ash-----------	6:6	0.0037	6	66	8	5.1	1.15	4.1 - 5.7
Aluminum------	6:6	.0814	<1	61	9	500	1.93	250 - 1,000
Arsenic-------	6:6	.0116	<1	33	7	.12	1.28	.10 - .15
Barium[1]-------	5:5	--	--	--	-	14	1.24	11 - 17
Boron---------	6:6	.0131	9	<1	0	9.1	1.30	7.8 - 12
Cadmium-------	6:6	.0909	9	21	0	.048	2.00	.022 - .15
Calcium-------	6:6	.0028	<1	*97	3	4,100	1.13	3,600 - 4,600
Chromium------	6:6	.0273	<1	<1	9	.71	1.46	.47 - .91
Cobalt--------	6:6	.0210	<1	<1	9	.23	1.40	.16 - .34
Copper--------	6:6	.0067	<1	<1	9	2.4	1.21	2.0 - 2.8
Europium------	3:6	--	--	--	-	[2].11	[2]2.30	<.082 - .33
Fluorine------	6:6	.0050	23	<1	7	7.8	1.18	6 - 9
Iron----------	6:6	.0311	<1	49	1	310	1.50	210 - 510
Lanthanum-----	4:6	.2187	5	<1	4	[2].72	[2]2.30	<.38 - 2.3
Lead----------	6:6	.0108	<1	19	1	1.4	1.27	1.0 - 1.8
Lithium-------	6:6	.0551	<1	<1	9	.29	1.72	.16 - .46
Magnesium-----	6:6	.0083	28	<1	2	1,000	1.23	820 - 1,200
Manganese-----	6:6	.0325	50	<1	9	50	1.51	31 - 74
Mercury-------	6:6	.0135	<1	82	7	.20	1.31	.15 - .25
Molybdenum----	6:6	.0123	19	4	7	.70	1.29	.48 - .90
Nickel--------	6:6	.0154	<1	75	5	.71	1.38	.49 - 1.1
Niobium-------	6:6	.0891	29	<1	1	.65	1.99	.26 - 1.3
Phosphorus----	6:6	.0033	52	17	1	340	1.14	260 - 390
Potassium-----	6:6	.0158	<1	44	6	2,400	1.34	1,600 - 3,500
Scandium------	6:6	.0148	<1	*97	3	.19	1.32	.14 - .24
Selenium------	6:6	.0027	14	<1	6	.096	1.13	.08 - .10
Sodium--------	6:6	.1119	40	<1	0	1,500	2.21	910 - 4,500
Strontium-----	6:6	.0090	<1	51	9	21	1.24	17 - 27
Sulfur (total)	6:6	.0061	41	<1	8	1,500	1.20	1,200 - 1,800
Titanium------	6:6	.1713	<1	70	0	16	2.59	5.3 - 44
Uranium-------	6:6	.0076	<1	73	7	.13	1.22	.10 - .16
Vanadium-------	6:6	.0278	<1	31	8	.94	1.47	.62 - 1.4
Ytterbium-----	3:6	--	--	--	-	[2].046	[2]1.32	<.038 - .068
Yttrium-------	6:6	.0261	<1	48	2	.47	1.45	.30 - .68
Zinc----------	6:6	.0131	5	<1	5	14	1.30	11 - 17
Zirconium-----	6:6	.1576	<1	45	5	1.9	2.49	.54 - 5.3

[1] Because of an erroneous concentration value, these statistics are based on five samples, not six.

[2] The technique of Cohen (1959) was used to calculate the mean and deviation because there were one or more concentration values outside of the limits of determination.

lead. These two elements differ somewhat from the elements shown in figure 10 because cobalt and lead have similar total levels between native soils and mine soils, but the extractable levels in mine soils (particu-



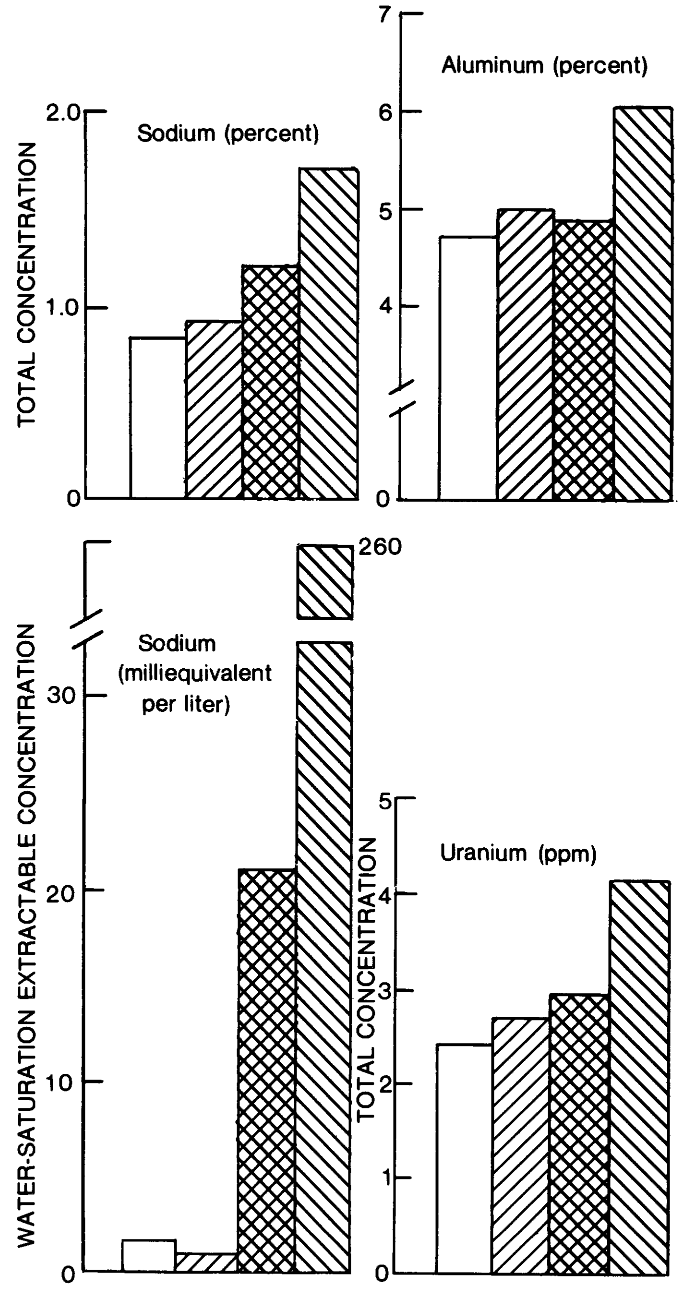


FIGURE 10. (above and right).— Differences between the average values for basin-wide native A- and C-horizon soils (47 samples) and replaced topsoil and spoil from the San Juan mine (12 samples) for extractable and total concentrations of copper, iron, manganese, and sodium, and total concentrations of aluminum and uranium (from Severson and Gough, 1981).

larly for cobalt) are much less than in native soils. Figure 12 shows the soil and spoil levels of boron and arsenic. These elements are notable because they show lower amounts in mine samples than in basin-wide samples, whereas the extractable boron in mine soil is greater.

In summary: (1) except for cobalt and lead, mine samples are higher in extractable-element concentrations than are basin-wide control samples; (2) both total- and extractable-element concentrations are generally higher in spoil samples than in native topsoil, native C-horizon soil, or replaced topsoil; and, (3) little difference was noted between the total amount of these elements in basin-wide A horizons of soil and in replaced topsoil at the mine; however, much greater differences were noted between the total amount of these elements in basin-wide C horizons of soil and in mine spoil.

Simple correlation analysis showed that few strong relations existed between extractable- or total-element concentrations in mine soil and mine-sampled plant-element concentrations. This fact, coupled with the

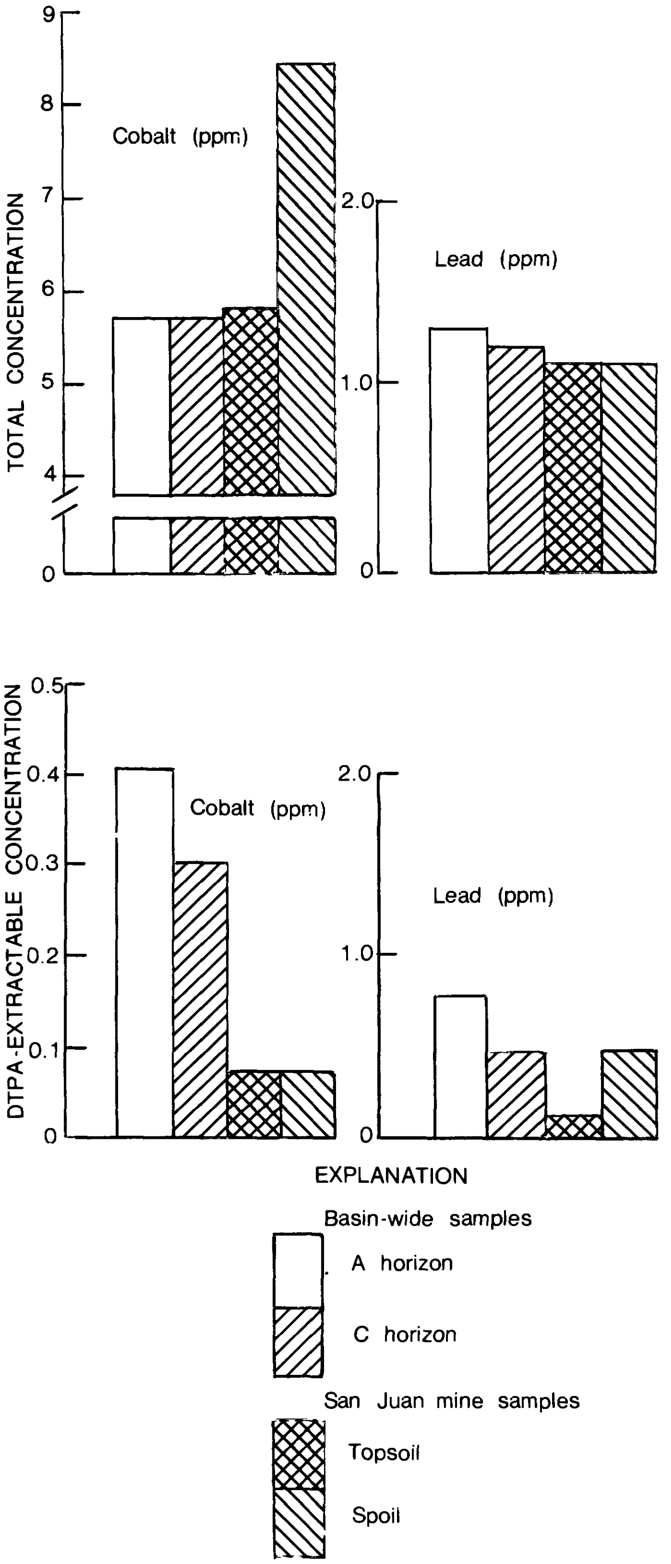


FIGURE 11. — Differences between the average values for basin-wide native A- and C-horizon soils (47 samples) and replaced topsoil and spoil from the San Juan mine (12 samples) for extractable and total concentrations of cobalt and lead (from Severson and Gough, 1981). <, less than.

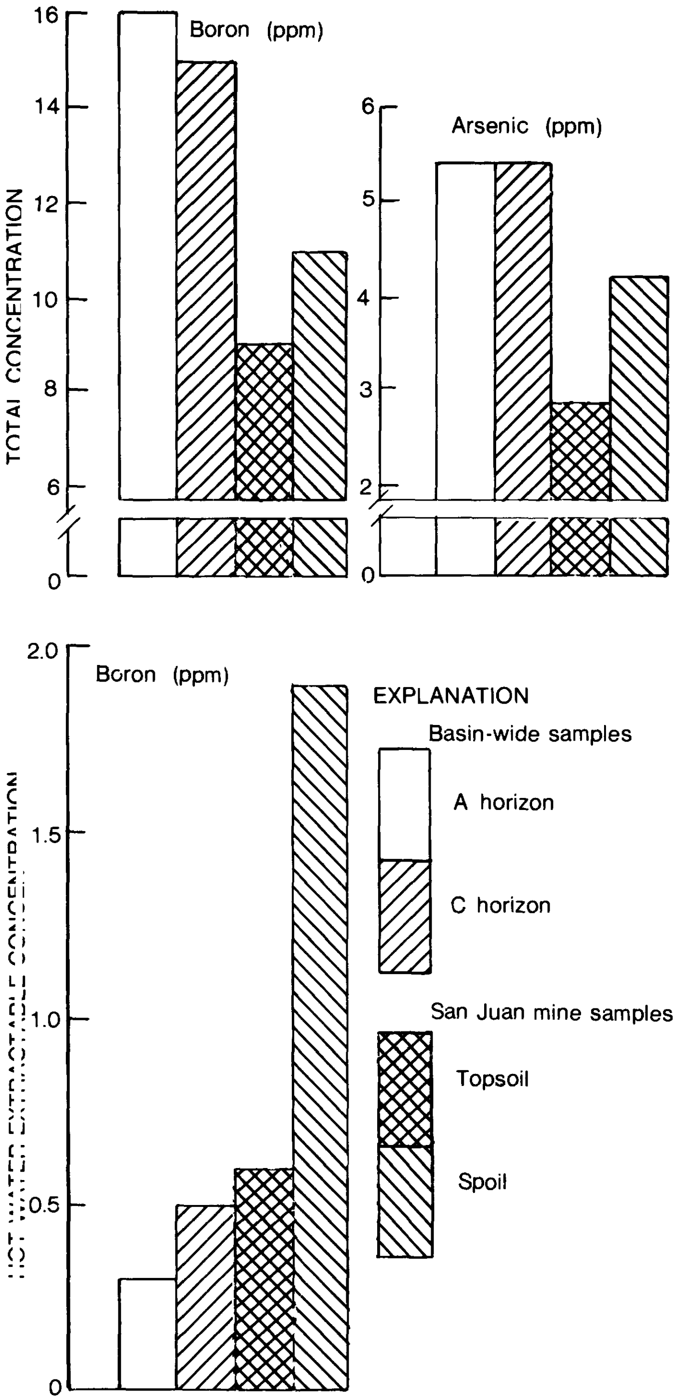


FIGURE 12. — Differences between the average values for basin-wide native A- and C-horizon soils (47 samples) and replaced topsoil and spoil from the San Juan mine (12 samples) for extractable and total concentrations of boron, and total concentrations of arsenic (from Severson and Gough, 1981).

small sample number of each material (n = 6), precludes the usefulness of prediction equations. Poor mine soil-plant element correlations occur, even though, compared with basin-wide soils, generally elevated extractable- and total-soil levels are reflected in elevated levels in mine-sampled plant material (table 2). Plant material analyses are, therefore, preferred to conventional soil analyses as indicators of element availability. This availability will vary with time, however, and the values we report for August 1977 will change as explained by Cornwell and Stone (1969, p. 118):

> Availability [in minesoils] is controlled not by storage and release from a relatively stable reserve, or an organic matter cycle, as in natural soils, but by rate of solution from fresh mineral surfaces or freshly-exposed subsoil particles. Hence, element availability cannot be predicted from tried and tested parameters such as pH, because relationships between the two are unknown for spoil bank materials.

A linear regression analysis between 10 soil and plant samples from the basin was possible, and such soil-plant relations under native conditions should be more stable with time than are relations under reclamation conditions. Prediction equations for native systems, therefore, are more reliable. As examples, the strong positive soil-plant availability relations for cobalt and copper follow:

$$\text{Log}_{10} \text{ basin saltbush cobalt} = -0.05 + 0.44 \log_{10} \text{ basin A-horizon DTPA-extractable cobalt } (r^2 = 0.67).$$

$$\text{Log}_{10} \text{ basin saltbush copper} = 3.1 + 1.8 \log_{10} \text{ basin A-horizon DTPA-extractable copper } (r^2 = 0.54).$$

Generally higher extractable levels in spoils (and not replaced topsoil) are assumed to be the source of the elevated levels of these elements in mine-sampled plants. An extreme example is sodium, which shows an increase of two orders of magnitude over basin wide C horizons of soil (fig. 10) that is also reflected by a similar increase of two orders of magnitude in sodium in mine-sampled saltbush (fig. 9). For a deep-rooted species like saltbush (Dayton, 1931, reported fourwing saltbush roots at a depth of 6 m below ground level), topsoiling to a depth of about 20 cm apparently does little to ameliorate the plant-uptake of elevated levels of some metals in spoil.

GEOGRAPHICAL DISTANCE-RELATED ELEMENT VARIABILITY

Tables 7 and 8 give estimates of the three components of distance-related variability in the element concentration of mine-sampled fourwing saltbush and alkali sacaton. These estimates are based on six samples and are therefore provisional. This variation is partitioned into components representing distances of 25–100 m, 5–25 m, and 0–5 m (local). The local component includes variation due to sample processing and analytical procedures (analytical error). Sixty-seven percent of the elements in saltbush (table 7) and 62 percent in sacaton (table 8) show that the local component accounts for 50 percent or more of the total variability. Excessive censoring of europium, lanthanum, and ytterbium concentrations in saltbush; europium and ytterbium in sacaton; and an error in one value for barium in sacaton, resulted in no AoV calculations for these elements. Several other elements in both saltbush and sacaton had values either above or below the detection limit for the analytical method used; however, no more than one-third of the values were substituted prior to the AoV calculation.

Even though the analytical-error component cannot be separated from the local component, it would appear that plants spaced relatively close together vary greatly in their element compositions. Thus, samples of saltbush and sacaton as far apart as 100 m will probably vary in their element composition little more than plants sampled only a few meters apart. This observation is undoubtedly a reflection of the heterogeneous composition and element availability of the spoil material from place to place in the rehabilitated area (Severson and Gough, 1981).

None of the elements in sacaton show a significant ($p < 0.05$) component of variability associated with a distance of 5-100 m, and only calcium and selenium are significant in saltbush for this distance. Therefore, calcium and selenium levels in saltbush differ over broad areas within the mine, whereas saltbush sampled close together varies only a little. Total calcium in replaced topsoil at the mine has significant variation at 25-100 m (Severson and Gough, 1981); and spoil material showed a large, but nonsignificant variation at 5-25 m. There appears, therefore, to be a correspondence between mine-soil calcium differences and saltbush calcium. Selenium occurs in concentrations too small to be commonly detected in soils by the methods we used, so saltbush-mine soil selenium comparisons are not possible. Several additional elements (boron, manganese, niobium, and zinc in saltbush; and calcium, europium, and scandium in sacaton) show significant variation at 5–25 m, and, therefore, plants separated by this distance can be expected to differ significantly in their composition of these elements. Further, sacaton has large but nonsignificant variation at 5-25 m for ash, aluminum, mercury, nickel, titanium, uranium, and ytterbium, whereas saltbush shows similar trends for ash, aluminum, magnesium, and scandium.

ELEMENT TOXICITY AND DEFICIENCY CONSIDERATIONS

Excess boron in alkaline and saline soils can adversely affect plant growth. Our boron data for the grass (sacaton) and for the shrub (saltbush) at the San Juan mine do not appear excessive when compared to similar material collected elsewhere in the western United States (U.S. Geological Survey, unpublished data). The total and hot-water extractable levels of boron in mine soils (GM for replaced topsoil, 0.6 ppm; spoil, 1.8 ppm) also indicate that boron toxicity problems are probably minimal — at least in the area we sampled. A few extractable values exceeded 2 ppm (toxicity threshold for some citrus species), and one value exceeded 11 ppm in spoil, which is high but probably not detrimental to nonagricultural species (Gough, Shacklette, and Case, 1979).

Boron levels in plant tissue are also diagnostic of potential plant toxicity problems. Boron concentrations in fourwing saltbush sampled at the mine are elevated (nearly double) when compared to basin-wide samples (tables 2 and 7). These values, however, do not exceed the range of values reported as suggestive of boron toxicity (Gough, Shacklette, and Case, 1979). Total boron in basin-wide soils is much greater than total boron in mine soils, yet the extractable levels of boron in the basin are far below those found at the mine (fig. 12). These levels suggest that in basin-wide soils boron is in a form (reservoir) not available to plants — this is certainly reflected by plant levels of boron (table 2). Mine spoil, however, is much higher in extractable boron than is mine topsoil, indicating that more boron in spoil should be available for plant uptake than in topsoil.

Mine soils, although highly variable, were predominantly alkaline, having a mean pH of 8.0 for topsoil and 7.6 for spoil. The observed pH ranges for topsoil and spoil, however, were 6.7-9.3 and 5.9-9.3, respectively. The occurrence of occasional low-pH soils at the mine may explain why mine-sampled plants were generally low in molybdenum and selenium when compared with basin-wide plant materials whose accompanying soils were never below a pH of 7.1 (tables 2, 7, and 8).

Erdman and others (1978) found that copper-molybdenum ratios (dry-weight basis) in sweetclover from rehabilitated spoil sites at eight mines in the northern Great Plains were low enough to warrant concern for the health of grazing ruminants. They pointed out that various metabolic imbalance diseases, generally termed "molybdenosis," are caused by either low copper in forage coupled with slightly elevated molybdenum or normal copper levels with very much higher molybdenum. They noted that copper-molybdenum ratios below about 5:1 are thought to be critical; therefore, they viewed with concern the ratios at these mines that ranged from about 0.4:1 to 5:1. Our copper-molybdenum ratios for alkali sacaton and fourwing saltbush at the San Juan mine varied greatly — ratios for saltbush were commonly more than 14:1 (due to relatively high copper levels), whereas those of sacaton ranged from 2.2:1 to 5.8:1. Because of these generally acceptable ratios and also because of uniformly low molybdenum concentrations (usually less than 1.0 ppm) in the plants sampled at the mine and throughout the basin, there appears to be little need for concern for potential molybdenosis in animals that might range over these rehabilitated areas. It should be noted that our mine and basin samples did not include any legumes, which are known to be generally higher in molybdenum than other forbs or grasses.

Figure 10 illustrates the large amount of extractable sodium in these soils. We reported in Chapter C (Severson and Gough, 1981) that the mine soils, in general, may be classified as saline sodic (U.S. Salinity Laboratory Staff, 1954) and possess the characteristics listed in table 9. Sodium-dominated alkaline soils are reported by Sandoval and Gould (1978) to have the following properties which are unfavorable to plant growth: (1) potential loss of phosphorus through the formation of highly soluble sodium phosphate compounds, (2) low availability of water because of either osmotic potential limitations, or decreased soil permeability properties, or both, (3) formation of undesireable sodium humates, and (4) inhibition of calcium, magnesium, and potassium uptake.

Possible deficiencies of elements essential to plant growth at rehabilitation sites were assessed both by the extractable levels in mine soils and by the levels in plant tissue. In Severson and Gough (1981) we reported

TABLE 9. —*Saline-sodic characteristics of San Juan mine soils (Study 3)*

Soil Parameter	Material	Geometric mean	Geometric deviation	Range
Water saturation extractable sodium----- (milliequivalents per liter)	Topsoil-- Spoil----	21 260	3.15 1.69	6.5-120 97 -500
Sodium adsorption ratio------------------	Topsoil-- Spoil----	7.6 51	2.26 1.56	2.7- 25 20 - 70
Exchangeable sodium percentage (percent)---	Topsoil-- Spoil----	4.8 32	2.48 1.68	1.5- 18 9.4- 49
Specific conductance----- (millimhos per centimeter)	Topsoil-- Spoil----	2.8 9.6	2.37 1.70	1.3- 11 4.0- 17

that extractable zinc levels in mine soils were low and potentially limiting to the growth of certain plants. Sacaton and saltbush, however, appear to be assimilating enough zinc, although the saltbush levels are four times greater than the levels in sacaton (tables 7 and 8). Potassium levels in sacaton appear unusually low for grasses in general (GM 0.24 percent) and may be depressed because of high levels of mine-soil sodium. Our X-ray fluorescence method for the determination of total phosphorus in soils registered concentrations for all of our samples below the detection limit of 0.5 percent. It is well known that low available phosphorus levels in reclamation soils can be limiting to plant growth. The phosphorus levels in both sacaton and saltbush appear somewhat depressed; however, their healthy appearance indicates that, for these species, available phosphorus is adequate. As cattle pasturage, the phosphorus levels of both species and the copper and zinc levels in sacaton are inadequate, whereas levels of cobalt (Hodgson and others, 1962), calcium, magnesium, iron, and manganese appear acceptable (Munshower and Neuman, 1978; Erdman and Ebens, 1979). Because the sacaton samples were washed and the saltbush samples were judged not to be excessively contaminated, these data represent material perhaps atypical of common forage. Grazing animals can greatly supplement their intake of trace metals by consuming vegetation with a coating of dust.

CONCLUSIONS

1. Samples of native galleta grass, broom snakeweed, and fourwing saltbush, from that part of the San Juan Basin most likely to be affected by energy development (Study 1), show large variability in their concentrations of 35 elements. The summary statistics for these elements can be used to judge the degree of change that future land-surface alterations may have on these plants. Plant-element composition, therefore, may be viewed as one measure of changes in the element availability in soils.
2. In Study 1, the concentrations of manganese, molybdenum, nickel, and uranium (and possibly iron and selenium) in galleta show regional trends. Concentrations of manganese, nickel, iron, and selenium are highest in the south-central part of the Study 1 area (selenium also shows high values just west and south of Farmington). The molybdenum and uranium data are unique, because two populations of values were defined. Concentrations of molybdenum in galleta were highest in the western edge of the study area, whereas uranium was highest in galleta samples collected west and southwest of Farmington.
3. Trends in the element composition of snakeweed and fourwing saltbush across the basin were not observed. For saltbush, however, the presence of such trends could not be measured because of too few samples. Of the species collected, however, saltbush exhibits the strongest relations between soil-plant element concentrations. For example, linear regressions for cobalt and copper between DTPA-extractable soil levels and plant levels explained 67 percent and 54 percent, respectively, of the total variability in the data.
4. Differences in the concentration of elements between Study 1 plant species are generally less than a factor of two except for the following: ash yield of saltbush is two times that of the other plants; boron in snakeweed and saltbush is four times greater than in galleta; iron in galleta is two times the levels found in saltbush; lead is much higher in galleta and snakeweed when compared to saltbush; the major essential elements calcium, magnesium, potassium, phosphorus, and sulfur are generally highest in saltbush; and selenium in saltbush is four times greater than the levels in galleta or snakeweed.
5. For plants growing in the Sheppard, Shiprock, and Doak soil series (Study 2), the GM, GD, observed range, and 95-percent expected range (baseline) for the concentration of 31 elements (and ash yield) in galleta and 32 elements (and ash yield) in snakeweed are given (tables 4 and 5). Concentrations of aluminum, iron, sulfur, vanadium, and zirconium in galleta, however, show a significant regional (more than 10 km) variance component, indicating that the baseline estimates are biased if compared to a newly collected sample from a specific area of Study 2. They are unbiased, however, if the baseline is used to estimate the most typical concentrations from the entire Study 2 area.
6. Most of the variability in the element-concentration data from Study 2 was at the distance increment of less than 0.1 km. This means that samples of galleta and snakeweed further apart than 10 km vary in their element composition little more than plants sampled as close together as 0.1 km. For most elements, therefore, the

analysis of only a very few samples of these two species can effectively characterize their element composition for a rather large area.

7. In Study 2, the southeasternmost cluster of galleta samples (barbell 3) is generally lowest in the concentration of nearly half of the elements analyzed, however snakeweed does not show a similar trend.
8. The concentrations of 35 elements (and ash yield) in alkali sacaton and fourwing saltbush collected on a spoil rehabilitation plot at the San Juan mine (Study 3, tables 7 and 8) are compared to samples of similar material from native (control) sites from throughout the San Juan Basin. Concentrations of aluminum, arsenic, boron, cobalt, copper, fluorine, iron, lead, manganese, sodium, and uranium in samples of saltbush growing over spoil generally exceed the levels of these elements in control samples. These element levels are elevated in plant samples from spoil sites by factors of from two to five times. Sodium concentrations in saltbush, however, are 100 times higher on spoil sites; and on the same sites the extractable-sodium levels in spoil material are also 100 times higher than C-horizon controls.
9. Simple correlation analysis shows that few significant positive correlations exist between either extractable- or total-element concentrations in mine soils and plant-element concentrations. Poor correlations occur even though generally elevated levels of elements are found in both the mine soils (extractable and total forms) and the mine-sampled plants. The generally higher extractable levels in spoils (and not replaced topsoil) are assumed to be the source of the elevated levels of these elements in mine-sampled plants.
10. Mine-sampled plants, spaced relatively close together (5 m or less), vary greatly in their element compositions. This variation reflects the heterogeneous composition and element availability of the spoil material.
11. As pasturage for cattle, mine-sampled fourwing saltbush is low in phosphorus, and sacaton is low in copper and zinc. Levels of cobalt, calcium, magnesium, iron, and manganese appear adequate in both plant species. No potential element-toxicity problems for grazing animals were noted. Except for some high boron and sodium levels, the mine soils do not contain element levels that are judged to be potentially toxic to native plant growth and development.

REFERENCES CITED

Aldon, E. F., and Springfield, H. W., 1973, Revegetating coal mine spoils in New Mexico: U.S. Department of Agriculture, Forest Service Research Note RM-245, 4 p.

——— 1975, Problems and techniques in revegetating coal mine spoils in New Mexico, *in* Wali, M. K., ed., Practices and problems of land reclamation in western North America: Grand Forks, N. Dak., University of North Dakota Press, Grand Forks, p. 122-132.

Barnes, F. C., and Arnold, F., 1951, Proved and potential oil and gas traps of the San Juan Basin: New Mexico Geological Society, Guidebook, Second Field Conference, p. 132-140.

Cohen, A. C., Jr., 1959, Simplified estimators for the normal distribution when samples are singly censored or truncated: Technometrics, v. 1, p. 217-237.

Cornwell, S. M., and Stone, E. L., 1969, Spoil type lithology and foliar composition of *Betula populifolia*, *in* Hutnik, R. J., and Davis, G., eds., Ecology and reclamation of devastated land: New York, Gordon and Breach, p. 105-118.

Crock, J. G., and Severson, R. C., 1980, Four reference soil and rock samples for measuring element availability in the western energy regions: U.S. Geological Survey Circular 841, 16 p.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Dayton, W. A., 1931, Important western browse plants: U.S. Department of Agriculture Miscellaneous Publication 101, 214 p.

Elmore, F. H., 1976, Shrubs and trees of the southwest uplands: Globe, Ariz., Southwest Parks and Monuments Association, 214 p.

Erdman, J. A., 1978, Potential toxicological problems associated with strip mining, *in* U.S. Geological Survey, Geochemical survey of the western energy regions, 5th annual progress report, July, 1978: U.S. Geological Survey Open-file Report 78-1105, p. 117-125.

Erdman, J. A., and Ebens, R. J., 1979, Element content of crested wheatgrass grown on reclaimed coal spoils and on soils nearby: Journal of Range Management, v. 32, p. 159-161.

Erdman, J. A., Ebens, R. J., and Case, A. A., 1978, Molybdenosis — a potential problem in ruminants grazing on coal mine spoils: Journal of Range Management, v. 31, no. 1, p. 34-36.

Erdman, J. A., and Gough, L. P., 1977, Variation in the element content of *Parmelia chlorochroa* from the Powder River Basin of Wyoming and Montana: The Bryologist, v. 80, p. 292-303.

Erdman, J. A., Shacklette, H. T., and Keith, J. R., 1976, Elemental composition of selected native plants and associated soils from major vegetation-type areas in Missouri: U.S. Geological Survey Professional Paper 954-C, 87 p.

Fassett, J. E., and Hinds, J. S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Professional Paper 676, 76 p.

Fenneman, N. M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co., Inc., 534 p., 1 map separate.

Gough, L. P., Severson, R. C., and McNeal, J. M., 1979, Extractable and total-soil element concentrations favorable for native plant growth in the northern Great Plains, *in* Wali, M. K., ed., Ecology and coal resource development: New York, Pergamon Press, p. 859-869.

Gough, L. P., Shacklette, H. T., and Case, A. A., 1979, Element concentrations toxic to plants, animals, and man: U.S. Geological Survey Bulletin 1466, 80 p.

Gould, W. L., Miyamoto, S., and Rai, Dhanpat, 1977, Reclamation potential of overburden materials in the Fruitland Formation in the San Juan Basin: New Mexico State University Agricultural Experiment Station Bulletin 657, 39 p.

Gould, W. L., Rai, Dhanpat, and Wierenga, P. J., 1975, Problems in reclamation of coal mine spoils in New Mexico, *in* Wali, M. K., ed., Practices and problems of land reclamation in western North America: Grand Forks, N. Dak., The University of North Dakota Press, p. 107-121.

Harms, T. F., 1976, Analysis of plants and plant ashes by methods other than emission spectroscopy, *in* Miesch, A. T., Geochemical survey of Missouri, methods of sampling, laboratory analysis, and statistical reduction of data: U.S. Geological Survey Professional Paper 954-A, p. 17-18.

Hilpert, L. S., 1969, Uranium resources of northwestern New Mexico: U.S. Geological Survey Professional Paoer 603, 166 p.

Hodgson, J. F., Leach, R. M., Jr., and Allaway, W. H., 1962. Micronutrients in soils and plants in relation to animal nutrition: Agriculture and Food Chemistry, v. 10, no. 3, p. 171-174.

Lindsay, W. L., and Norvell, W. A., 1978, Development of a DTPA soil test for zinc, iron, manganese, and copper: Soil Science Society of America Journal, v. 42, no. 3, p. 421-428.

Maker, H. J., Folks, J. J., Anderson, J. U., and Link, V. G., 1973, Soil associations and land classification for irrigation, Rio Arriba County: New Mexico State University Agricultural Experiment Station Research Report 254, 69 p.

Maker, H. J., Keetch, C. W., and Anderson J. U., 1973, Soil associations and land classification for irrigation, San Juan County: New Mexico State University Agricultural Experiment Station Reseach Report 257, 44 p.

Miesch, A. T., 1976, Geochemical survey of Missouri — methods of sampling, laboratory analysis, and statistical reduction of data in a geochemical survey of Missouri, with sections on laboratory methods: U.S. Geological Survey Professional Paper 954-A, 39 p.

Munshower, F. F., and Neuman, D. R., 1978, Elemental concentrations in native range grasses from the northern Great Plains of Montana: Journal of Range Management, v. 31, no. 2, p. 145-148.

Natrella, M. G., 1966, Experimental statistics: Washington, D.C., U.S. Department of Commerce, National Bureau of Standards Handbook 91 (pages not numbered consecutively).

Sandoval, F. M., and Gould, W. L., 1978, Improvement of saline- and sodium-affected disturbed lands, *in* Reclamation of drastically disturbed lands: Madison, Wis., American Society of Agronomy, p. 485-504.

Severson, R. C., and Gough, L. P., 1981, Geochemistry and variability of natural and mine reclaimed soils in the San Juan Basin, New Mexico: U.S. Geological Survey Professional Paper 1134-C.

Severson, R. C., and Tidball, R. R., 1979, Spatial variation in total element concentration in soil within the Northern Great Plains coal region: U.S. Geological Survey Professional Paper 1134-A, 18 p.

Shomaker, J. W., Beaumont, E. C., and Kottlowski, F. E., eds., 1971, Strippable low-sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, 189 p.

Tidball, R. R., 1976, Chemical variation of soils in Missouri associated with selected levels of the soil classification system: U.S. Geological Survey Professional Paper 954-B, 16 p.

Tidball, R. R., and Ebens, R. J., 1976, Regional geochemical baselines in soils of the Powder River Basin, Montana-Wyoming, *in* Laudon, R. B., ed., Geology and energy resources of the Powder River Basin: Wyoming Geology Association, 28th Annual Field Conference, Casper, Wyo. Guidebook, p. 299-310.

Tourtelot, H. A., and Miesch, A. T., 1975, Sampling designs in environmental geochemistry: Geological Society of America Special Paper 155, p. 107-118.

U.S. Department of Energy, 1980, A survey of coal mining capacity in the West: U.S. Department of Energy, Western Coal Development Monitoring System, Publication DOE/RA-0045, 37 p.

U.S. Department of the Interior, 1976, Resource and potential reclamation evaluation, Bisti West study site, Bisti Coal Field: Washington, D.C., Energy Mineral Rehabilitation Inventory and Analysis (EMRIA) Report 5, 108 p., 6 appendixes.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.

VanTrump, George, Jr., and Miesch, A. T., 1977, The U.S. Geological Survey RASS-STATPAC system for management and statistical reduction of geochemical data: Computers and Geoscience, v. 3, p. 475-488.

West, N. E., ed., 1972, Galleta--taxonomy, ecology, and management of *Hilaria jamesii* on western rangelands: Utah Agricultural Experiment Station Bulletin 487, 38 p.

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