Selenium in Soils and Plants from Native and Irrigated Lands at the Kendrick Reclamation Project Area, Wyoming

By J.A. Erdman, R.C. Severson, J.G. Crock, T.F. Harms, *and* H.F. Mayland

ABSTRACT

In response to earlier findings of elevated levels of selenium in the Kendrick area, two detailed geochemical surveys were conducted in 1988 to study the distribution of selenium in soils (0–1 m depth), and new growth of associated big sagebrush (*Artemisia tridentata* Nutt.) and alfalfa (*Medicago sativa* L.). A survey of the native rangeland focused on specific geologic units as sources of selenium; whereas, a gridded survey of the irrigated lands assessed the extent of its mobilization, transport, and concentration.

Only three of the approximately 200 soil samples contained total selenium slightly greater than the 3.3 ppm maximum baseline established for soils from the northern Great Plains. In contrast, selenium concentrations in about one-fifth of the big sagebrush samples exceeded the 1.1 ppm maximum baseline established for this species from the West. Selenium tended to be elevated, but not uniformly so, in both soils and sagebrush collected from areas underlain by the Cody Shale of Cretaceous age.

Alfalfa from about 15% of the irrigated fields contained selenium in excess of about 4 ppm, levels reported to be potentially hazardous to livestock if fed over prolonged periods. Most of these samples were concentrated in an area of 11 contiguous sections where selenium-enriched surface and drain waters also occurred. The agricultural soils just to the north of this seleniferous area had slightly higher levels of selenium compared to those elsewhere in the irrigated lands. At present, the cause for this displaced anomaly is unclear.

Followup sampling in 1989 of two fields where selenium levels in alfalfa collected in 1988 were 25 and 15 ppm yielded samples that contained only 0.2 and 0.7 ppm, respectively. This dramatic and puzzling temporal disparity may be explained by marked differences in weather patterns and irrigation practices for the 2 years. Such a disparity underscores the need to monitor a potentially seleniferous area over an extended period.

INTRODUCTION

The Kendrick Reclamation Project Area was one of nine areas selected in 1985 by the Department of Interior for a field-screening study to investigate the possibility of elevated selenium concentrations in irrigation drainage. This reconnaissance investigation of the Kendrick area showed anomalous levels of selenium in bottom sediments (Severson and others, 1987b), water, and biota (Peterson and others, 1987).

On the basis of these findings, the Department of Interior's Irrigation Drainage Task Group selected Kendrick as one of four areas for more detailed study. Detailed studies focus on the following goals: (1) determine the magnitude and extent of irrigation-induced water quality problems, and (2) provide the scientific understanding needed to mitigate or resolve identified problems. The working objective for each of the four detailed studies was to determine the extent, magnitude, and effects of contaminants associated with agricultural drainage, and, where effects are documented, to determine the sources and exposure pathways that cause contamination.

In the mid-1930's, the Bureau of Reclamation began the Kendrick irrigation and drainage project in Natrona County, Wyoming (fig. 1). An area of approximately 24,000 acres near Casper, Wyoming, has been under irrigation since about 1946.

Two detailed geochemical surveys were conducted in 1988 to study the distribution of selenium and other elements in native and agricultural soils and plants of the Kendrick Reclamation Project Area (hereafter abbreviated to "Kendrick Project").

The native, nonirrigated soils have developed on different geologic units, including several marine Cretaceous formations containing carbonaceous shales and coals (Mesaverde Formation, Lance Formation, Meeteetse Formation and Lewis Shale [combined], and the Niobrara Formation), and several Tertiary formations containing bentonite, claystone, shale, and sandstone or siltstone (White River Formation, Wind River Formation, and the Fort Union Formation). A study that focused on the local geology was judged essential to identify specific geologic

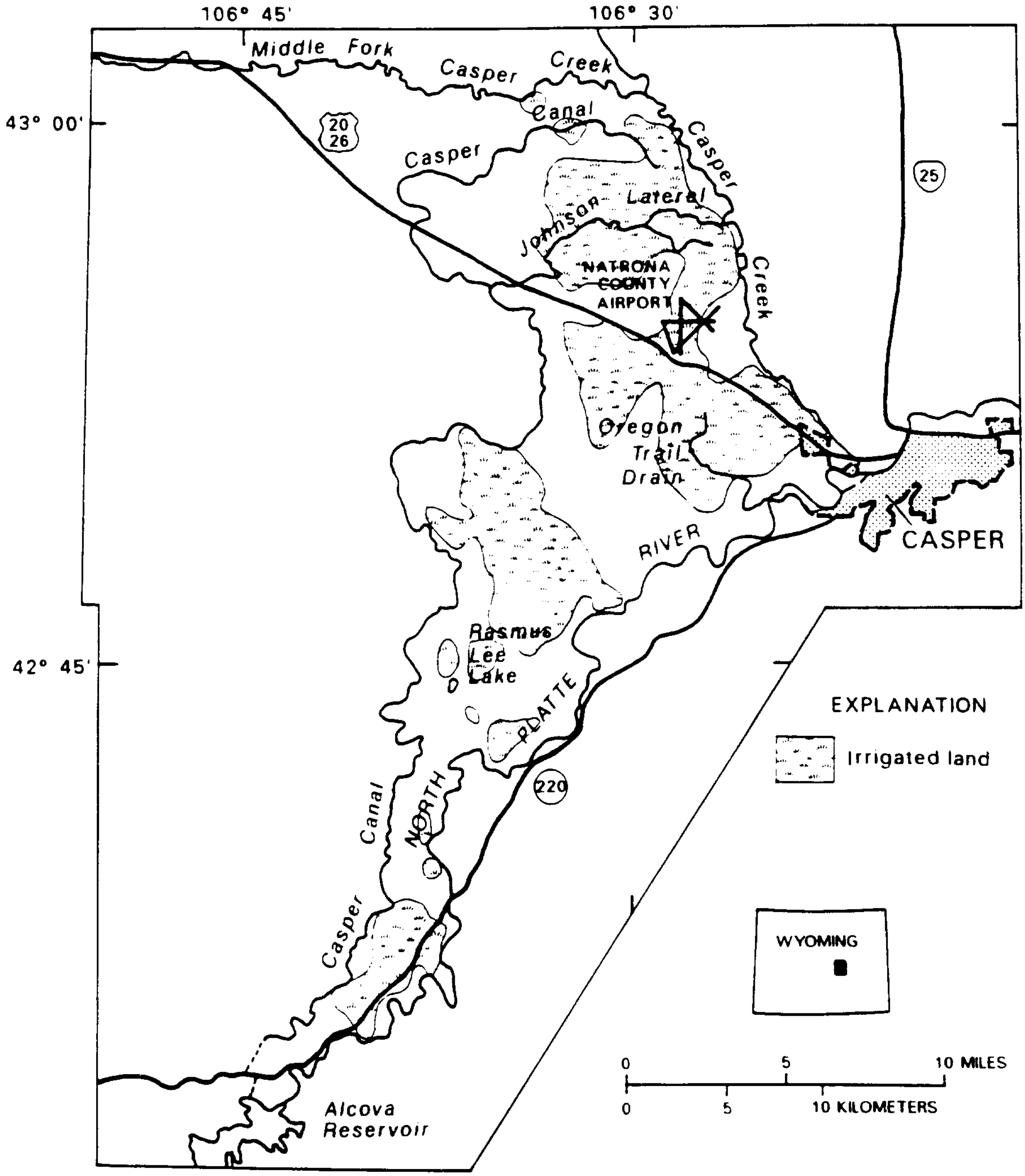

Figure 1. Index map of the Kendrick Reclamation Project Area.

units as sources of the elevated selenium found in the screening studies. A geologic map of the Kendrick Project, simplified from a map of Natrona County (Lageson, 1980), is shown in figure 2.

The agricultural portion of the Kendrick Project comprises a patchwork of irrigated land surrounded by uncultivated native rangeland. Irrigated soils are generally confined to two dominant geologic units: Cody Shale of Cretaceous age and Quaternary alluvial deposits. The alluvium is derived largely from the Cody Shale. We felt that information on agricultural soils and alfalfa might reveal the extent of mobilization, transport, and concentration of selenium and other trace elements resulting from irrigation.

A synthesis of the results from both detailed geochemical studies might serve to segregate the effects of irrigation from those attributed to natural environmental processes.

These soil and plant surveys were conducted concurrently with independent water and wildlife surveys

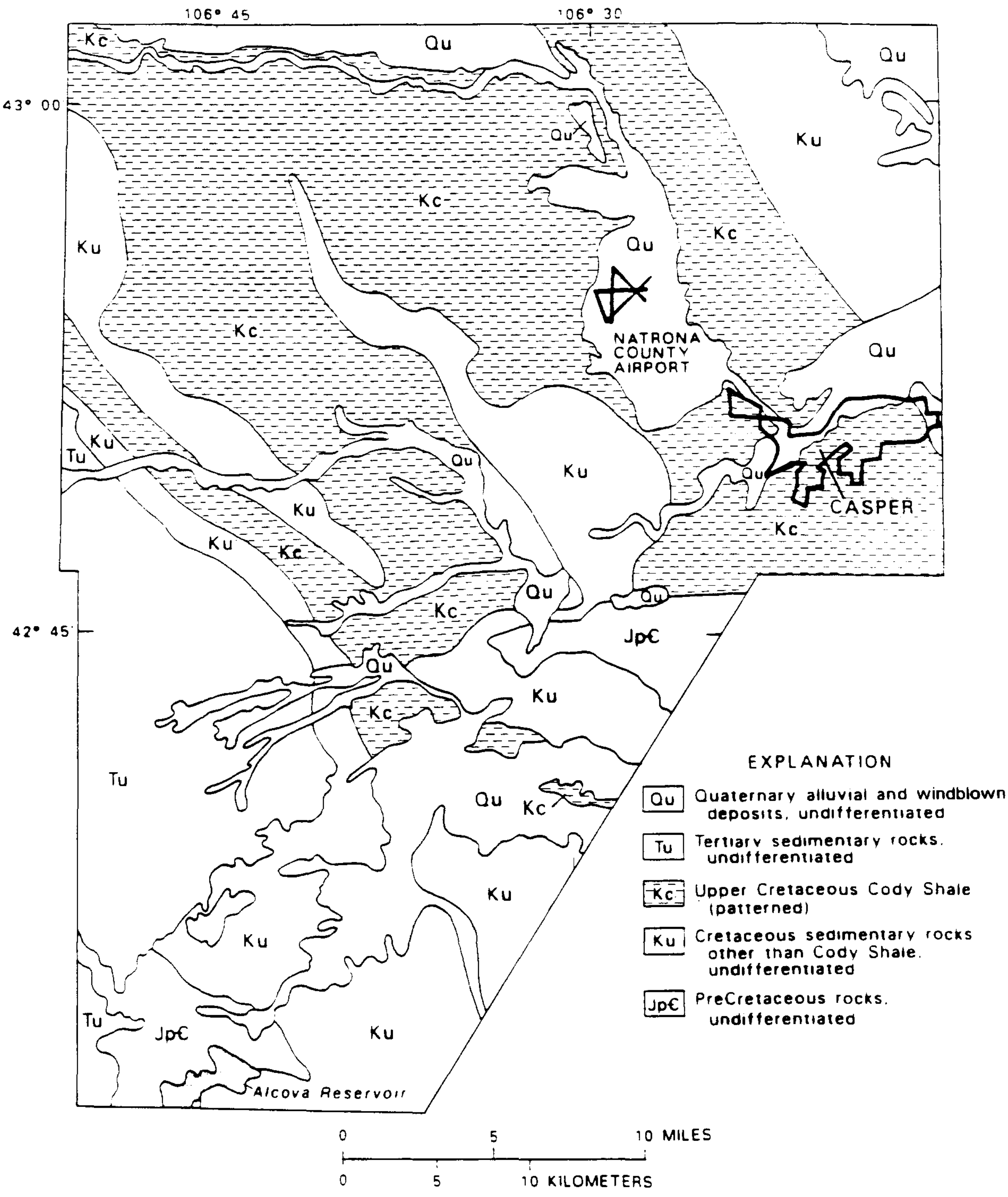

Figure 2. Simplified geologic map of the Kendrick Reclamation Project Area (adapted from Lageson, 1980).

by personnel of the Water Resources Division (USGS) and the United States Fish and Wildlife Service, respectively. A future summary report will integrate the results of this multidisciplinary effort.

The intent of the present report is to discuss the significance of the selenium data that were released earlier (Erdman and others, 1989).

METHODS

Field Sampling

Separate sampling plans were designed for the irrigated agricultural lands and the surrounding native rangelands. Field sampling was conducted by Severson, Erdman, and Crock during the spring and early summer of 1988.

Native Soils and Big Sagebrush

A four-level, stratified random sampling design was used to assess the variability in trace element content of native soils and big sagebrush (*Artemisia tridentata* Nutt.) among and within geologic units that occur in the Kendrick Project. The Kendrick Project area encompasses approximately 25 townships. Twelve of the townships were selected randomly for sampling (fig. 3). A total of 14 geologic units was identified for sampling within the area, but not all geologic units occurred in each township. The distribution of geologic units occurring within each township is shown in table 1. Within a township, each of the geologic units present was sampled at two randomly selected locations. A sampling location was chosen by randomly selecting a section with reasonable accessibility and by identifying the geologic units within that section. Successive sections were selected randomly within each township until all geologic units occurring within the township had been sampled twice.

The purpose of this geochemical survey was to identify the possible source rocks of selenium, not to produce geochemical maps. Two questions we sought to answer were (1) Is a specific geologic formation more seleniferous than others? (2) If so, is the selenium uniformly distributed throughout the unit?

Field work began April 12, 1988, and lasted almost the balance of the month. At each of the 120 sites selected, we used a 3.5-inch bucket auger to collect a sample of the uppermost meter of the soil horizon. The 1-meter channel sample was then mixed in the field and a 1-kg sample collected. Only 101 of the sites supported big sagebrush, thus resulting in 19 "non-response" sites for the plant portion of the study. The previous year's growth was clipped from several shrubs within about a 10-m radius of the soil-auger hole and placed in cloth HUBCO bags. Most plants were still essentially dormant at the time and many had been heavily browsed by antelope.

Estimates of analytical precision for the soils and sagebrush analyses were based on 15 splits and 10 splits, respectively.

Agricultural Soils and Alfalfa

Geobotanical mapping of areas of selenium deficiency and excess is a proven technique, as described recently by Combs and Combs (1986, p. 29):

> ***Kubota and others (1967) surveyed the distribution of selenium in more than 1000 samples of forages (primarily alfalfa) from different parts of the USA. They used the results of the survey to produce a generalized map of the distribution of selenium in United States crops. Because their map was based upon crop selenium data, it has greater relevance to considerations of nutritional aspects of selenium than would one based upon geological data, inasmuch as it represents the distribution of selenium in the particular terrain (i.e., valleys and plains) used for food and feed production.

On a much smaller but more detailed scale, we collected samples on an approximate grid-interval of 1 mile that would allow the preparation of geochemical maps identifying areas of low and high concentrations of selenium and other environmentally important trace elements, based on soils and alfalfa throughout the irrigated lands. An efficient sampling plan is dictated by an optimum grid size which, in turn, depends on knowing where most of the geochemical variation occurs spatially throughout the landscape. Because this information was unavailable for the Kendrick Project, we selected a grid size of 1 mile based on previous studies in the northern Great Plains (Severson and Tidball, 1979) and in the San Joaquin Valley (Severson and others, 1987a).

Although the irrigated lands of the Kendrick Project encompass about 38 square miles (sections), only portions of most sections are currently irrigated, and those portions under irrigation are not contiguous. We superposed a map of irrigated areas (1:24,000 scale), which lacked essential access details, over the appropriate topographic maps of the same scale. Sections that contained less than 40 acres of irrigated land were rejected. For the most part the locality selected in the office proved to be suitable to sample when we arrived at the site.

From June 7–17, 1988, we collected samples of soils and associated alfalfa (*Medicago sativa* L.), mostly in the 10% bloom stage, from fields in 109 sections, beginning at the south end of the Kendrick Project and completing the sampling at the north end. Four sections lacked any alfalfa, although evidence of previous irrigation required that we sample at least the soils. Alfalfa was sampled from 105 fields and soils from 109 fields.

Within each field, two sites approximately 100 meters apart were selected and sampled. In later preparation of the samples, half of each soil and alfalfa sample from the two within-field sites was retained for possible separate analysis while the other half was blended with its field pair; this composite sample was then analyzed. Each alfalfa sample was a collection of several individual plants within a few meters of the soil-auger hole. The top 20 cm of the plants were sampled. The 1-m soil core sample was similar to that described above for the native soils, but sampling often proved to be more time consuming especially in clay-rich soils that had been heavily irrigated.

A three-level analysis-of-variance design was incorporated into this geochemical study to estimate the within-field variance and analytical error. For the soils, the estimate of within-field variance was based on site pairs

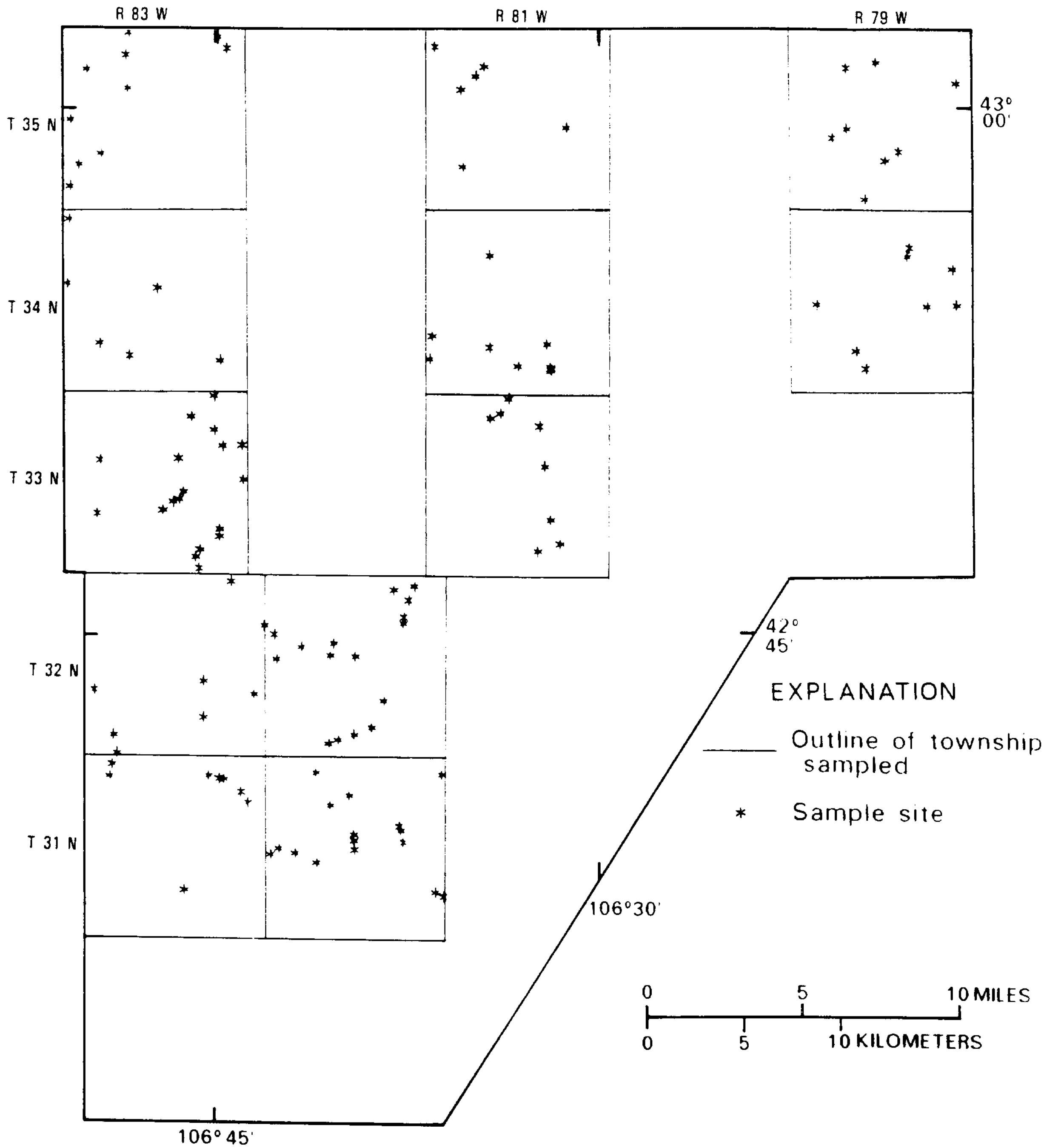

Figure 3. Locations of townships and sites sampled in the geologic-source study.

from eight fields, and analytical error was based on 15 analytical splits. For the alfalfa, site duplicates from seven fields were retained; each of the 14 samples was split in order to estimate the analytical error.

Field-sampling conditions were optimum: first cutting of the alfalfa was not to begin for another week, access to most fields was ideal, weather conditions were virtually perfect, and the selenium indicator plants, mainly two-grooved poisonvetch (*Astragalus bisulcatus* [Hook.] Gray) and woody aster (*Xylorrhiza glabriuscula* Nutt.), were at their peak bloom period.

On June 6, 1989, field sampling was repeated by H.F. Mayland in two localities where alfalfa, sampled in 1988, contained 15 and 25 ppm selenium. Both localities occur on Cretaceous Cody Shale. The forage mixtures contained about 85% alfalfa and 15% smooth bromegrass (*Bromus*

Table 1. Distribution of geologic units sampled from randomly selected townships at the Kendrick Reclamation Project Area

[Numbers in body of table indicate number of sample sites from each geologic unit within each township. Explanation of geologic units: Qal, Quatenary alluvium; Qs, Quaternary sand dunes; Twru, Tertiary White River, upper unit; Twrl, Tertiary White River, lower unit; Twdr, Wind River Formation; Tfu, Tertiary Fort Union Formation; Kl, Cretaceous Lance Formation; Kfh, Cretaceous Fox Hills Sandstone; Kml, Cretaceous Meeteetse Formation; Kmv, Cretaceous Mesaverde Formation; Kc, Cretaceous Cody Shale; Ks, Cretaceous Steele Shale; Kf, Cretaceous Frontier Formation; Kmt, Cretaceous Mowry and Thermopolis Shales]

Township North	Range West	Geologic Units													
				Twr											
		Qal	Qs	Twru	Twrl	Twdr	Tfu	Kl	Kfh	Kml	Kmv	Kc	Ks	Kf	Kmt
35	79	-	2	-	-	-	-	-	2	2	2	-	-	-	-
35	81	2	2	-	-	-	-	-	-	-	-	2	-	-	-
35	83	2	2	-	-	-	-	-	-	-	-	2	-	2	2
34	83	-	-	-	-	-	-	-	-	-	-	2	-	2	2
34	81	2	2	-	-	-	-	-	-	-	-	2	-	2	-
34	79	-	2	-	-	-	-	-	-	2	2	2	-	-	-
33	81	2	-	-	-	-	-	-	-	-	-	2	-	2	2
33	83	2	-	-	-	2	2	2	-	2	2	2	-	2	2
32	83	2	-	-	2	2	2	-	-	-	-	-	-	-	-
32	82	2	-	-	-	2	2	2	-	2	2	2	-	2	-
31	82	2	-	-	2	2	1	2	-	2	3	-	2	-	-
31	83	2	-	2	2	2	-	-	-	-	-	-	-	-	-

inermis Leyss.). Plants were 30- to 35-cm tall and were in early bud and flower stage, respectively. The first harvest of the season occurred 2 weeks after sampling. Selenium indicator plants in this area were in early bloom stage.

Two to four tillers (above 4-cm stubble height) each of alfalfa and bromegrass were collected from each of approximately 50 subsites on each of four sampling sites. One of these sites was a 40-acre field having 1.5% slope and easterly aspect. The three remaining sites were part of a 40-acre field containing 10 acres having 2–3% slope on a northerly aspect and an upper and lower site on the other 30 acres, having a 2–4% slope and a southeasterly aspect.

Laboratory Methods

Sample Preparation

Soil samples were sent to the United States Geological Survey laboratories in Denver for preparation and analysis. After the samples were air dried under forced air at ambient temperatures, they were disaggregated with a mechanical mortar-and-pestle, sieved at 2 mm (10 mesh), and the minus 2 mm material saved for analyses. A split of the minus 2 mm material was ground in a ceramic plate grinder to minus-100 mesh, and this material was used for all chemical analysis.

All plant samples were washed (to avoid any possible surface contamination), dried, and pulverized to a 2-mm size in a Wiley mill by the sample preparation laboratory of Minerals Exploration Geochemistry, Carson City, Nevada. Drying was at ambient temperature for 24 hours followed by 15 minutes in a microwave oven. The alfalfa samples were mailed in the cloth sample bags to the preparation laboratory within 1–2 days of collection.

After milling, 10 of the 101 sagebrush samples collected from the native rangeland were split into two parts in the laboratory to provide an estimate of the analytical precision. The total number of sagebrush samples, then, was 111; these were submitted for analysis to the United States Geological Survey laboratories in Denver in a randomized sequence.

The alfalfa samples from each site (two sites per field) were separated into two parts with a Jones splitter, and one part of each field pair was then combined for analysis. The other part of each pair was placed in the original sample bag to allow for later analyses of the site samples, if needed. Alfalfa samples from two sites in each of seven fields were analyzed separately in order to estimate local variation. Splits of these 14 samples were made to estimate analytical error. The total number of alfalfa samples was 126; these samples came from 105 fields.

The 1989 forage samples were cut into 1- to 2-cm lengths, mixed thoroughly, subdivided into approximately 200 g subsamples, and submitted to one of three drying methods: (1) oven drying in forced draft (100°C for 90 minutes followed by 65°C for 30 hours), (2) microwave drying (200 g sample for 15 minutes in 1.22 kw household microwave oven at 2450 MHz), and (3) freeze drying. Samples were then ground to pass a 1-mm sieve in an intermediate Thomas-Wiley mill.

Analytical Techniques

The selenium analyses were performed by two techniques: continuous-flow hydride generation atomic absorption spectroscopy (HGAAS) for soils (Crock and Lichte, 1982; Sanzolone and Chao, 1987), and fluorometry for plants (Harms and Ward, 1975).

A 0.25-gram soil sample was digested with nitric, perchloric, and hydrofluoric acids. After digestion, the sample was diluted to 50 mL with 6*N* HCl. In the procedure, the sample solution was reacted with sodium borohydride in order to generate the gaseous hydride which was swept into the heated quartz furnace of an atomic absorption spectrometer. Selenium was determined using an aqueous standard calibration curve. The determination limit for selenium in soils is 0.1 ppm. The relative standard deviation for duplicate determinations was about 10%.

One gram of dried, ground vegetation was digested with 10-ml nitric and 2-ml perchloric acids; hydrogen peroxide was used to help break down resistant waxes. Selenium was then complexed with 2,3-diaminonaphthalene, and the complex extracted into cyclohexane. The determination limit for selenium in plants is 0.01 ppm; the relative standard deviation for duplicate determinations was 10–15%.

Selenium concentrations in the 1989 forage samples were determined by HGAAS after a similar digestion was used for the fluorometric determination. Several forage samples, including the two collected from the same areas in 1988, were included as unknowns with the 1989 sample set.

Quality Control

Soil Materials

Statistical techniques and reference samples were used to assess accuracy and precision of the selenium analyses. Subsets of samples from each of the two geochemical studies were selected to be split into two parts after grinding and analyzed separately to estimate errors associated with sample preparation and analysis (often referred to as procedural error rather than analytical error). The samples from each study, plus sample splits, were arranged in a randomized sequence and prepared and analyzed in that sequence to convert any systematic errors in preparation and analysis to random errors, and to estimate relative laboratory precision. Samples of United States Geological Survey standard reference material SCo-1 Cody Shale were inserted at random intervals into the soil-sample sequence to estimate laboratory accuracy. Reported consensus values from the literature, when compared with our laboratory determinations (table 2), show that the determinations were highly accurate.

Plant Materials

Several biological standard reference materials from the National Bureau of Standards were analyzed for selenium by the fluorometric method. Gladney (1980) analyzed these same materials by neutron activation analysis. The close agreement between the certified values, the values determined by Gladney (1980), and those determined by the United States Geological Survey laboratories are shown in table 2.

RESULTS AND DISCUSSION

Geologic Units In Native Rangeland

Native Soils

Background ranges for selenium in soils of the northern Great Plains, as well as those for soils from three other regional studies in the West, are given in table 3. An explanation of the data in table 3 is necessary before any comparisons can be made. The computed values are referred to as baselines rather than backgrounds because they represent the concentration measured at some point in time. Background values, in contrast, are intended to represent natural concentrations that exclude man's influence, and are rarely obtainable. The sampling media for each of the studies in table 3 differ from one study to another. Samples from the western half of the United States (Shacklette and Boerngen, 1984) were collected from the B horizon, or below 20 cm where the B horizon was undefined. Surface or A-horizon samples were collected for the northern Great Plains study (Severson and Tidball, 1979). And the surface 0–20 cm was collected for the San Joaquin Valley study (J.M. McNeal, United States Geological Survey, Reston,

Table 2. Analysis of standard reference materials for selenium

[All values are expressed in parts per million]

Reference materials	National Bureau of Standards certified values	Literature values	This study determined values
SCo-1 (Cody Shale)[1]	Not determined	0.89±(0.06)[4]	0.82±(0.117)[6]
#1567 Wheat flour[2]	1.1±(0.2)	1.12±(0.01)[5]	0.97
#1571 Orchard leaves[2]	0.08±(0.01)	0.08±(0.009)[5]	0.075
#1575 Pine needles[2]	Not determined	0.049±(0.004)[5]	0.056
#1570 Spinach[2]	Not determined	0.039±(0.015)[5]	0.032
#1572 Citrus leaves[2]	0.025[3]	Not determined	0.038±(0.002)[7]

[1] U.S. Geological Survey reference material.
[2] National Bureau of Standards reference material.
[3] Non-certified value.
[4] Gladney and Roelandts, 1988.
[5] Gladney, 1980.
[6] Based on six analyses.
[7] Based on five analyses.

VA, unpubl. data, 1987). Samples of soils from a depth of 66–72 inches were collected from the Panoche Fan, located on the west side of the San Joaquin Valley, California (Severson, Tidball, and Wilson, 1987). These baselines are valid for comparing analyses of the same kind of sample from within the area where the baseline was developed. They should be applied with caution to different sample media or to samples collected outside of the baseline area. They are presented here to show what ranges in selenium values have been determined in soils from different parts of the Western United States.

Additional data on selenium in world soils are summarized by Berrow and Ure (1989). Some reported values for soils exceed those shown in table 3 (this report).

All the native, rangeland soils that we sampled contained total selenium within the 3.3 ppm norm established for soils from the northern Great Plains (fig. 4), the most appropriate baseline with which to compare our data. The relative normalcy of the Kendrick soils is quite surprising in light of the clearly anomalous concentrations of selenium found in the associated sagebrush collected in our study. A comparison of the ranges and means for selenium in soils collected from the various geologic units (fig. 4) shows that soils from the Cody Shale are higher in selenium than those from the other units, and only the mean from the Cody Shale exceeds that for soils from the northern Great Plains.

Results of the analysis-of-variance, expressed as a percent of the total variance, are as follows:

	Geologic Units	Townships	Sections	Analyses
Native soils	34*	11	45*	10

*Differences within a category are significant at the 0.05 level.

An F-test of the variance components shows statistically significant differences in selenium concentrations in the native soils among geologic units and between sections within townships. This result suggests that the geology plays an important role as a source of selenium, but a specific unit, such as the Cody Shale, is not uniformly seleniferous. In fact, the small-scale variation that occurs between sites from randomly selected sections in townships exceeds that between geologic units. (For the few samples in which selenium was reported to be less than the detection limit, we replaced the "less than" values with an arbitrary

Table 3. Geochemical baselines for selenium in soils from selected studies in the Western United States

[Detection ratio, number of samples in which the element was found in measurable concentrations to number of samples analyzed; GM, geometric mean; GD, geometric deviation; baseline, expected 95-percent range]

Reference and general location of the study area	Detection ratio	GM	GD	Baseline	Observed range
Shacklette and Boerngen (1984) western half of the United States.	590:733	0.23	2.43	0.039-1.4	<0.1-4.3
Severson and Tidball (1979) northern Great Plains, parts of Montana, Wyoming, and N. Dakota.	104:136	0.45	2.72	0.061-3.3	<0.1-20
McNeal (unpublished data) San Joaquin Valley, California.	240:328	0.14	2.56	0.021-0.92	<0.1-2.8
Severson, Tidball, and Wilson (1987) Panoche Fan, San Joaquin Valley.	713:721	0.68	1.94	0.1-2.2	<0.1-4.5

value of 0.07 ppm; noncensored data are required in the analysis-of-variance.) Analytical error contributed only 10% of the total variance; the analytical precision, then, was quite satisfactory.

Big Sagebrush

In the Kendrick Project, the geometric mean for selenium in big sagebrush is 0.41 ppm—four times higher than the norm of 0.11 reported by Gough and Erdman (1983) for big sagebrush from the Western United States. Concentrations of selenium in sagebrush from the Kendrick Project ranged from 0.06–9.5 ppm (fig. 5), the maximum value far exceeding the 1.1 ppm upper baseline threshold. A total of 13 samples exceeded the normal range expected, and the four clear outliers—9.5, 7.5, 6.5, and 5.5 ppm—came from sites mapped as Cody Shale. Our results indicate that sagebrush from the Cody Shale typically contains selenium at levels close to the upper limit of the normal range (fig. 5).

If we look at selenium in big sagebrush from the nearby Powder River Basin, however, the concentrations in sagebrush from the Kendrick Project are not quite so extreme. In a reconnaissance study of the Powder River Basin of Wyoming and Montana, Connor and others (1976) reported a geometric mean of 0.43 ppm selenium, almost identical to that for sagebrush from the Kendrick Project, and an observed range of 0.08–4.8 ppm for samples of sagebrush from 41 localities.

As with the native soil results, the most seleniferous vegetation comes from areas underlain by Cody Shale. In contrast to the soil results, many of the sagebrush samples contained anomalous levels of selenium when compared to norms. Yet some of the sagebrush sampled from the Cody Shale contained the lowest concentrations. Sagebrush from five other geological units, including alluvium deposits of Quaternary age, also contained selenium that exceeded the established baseline. Low-selenium sagebrush tended to occur at sites mapped as Quaternary alluvium or dune-sand deposits.

Results of the analysis-of-variance, expressed as a percentage of the total variance, are given as follows:

	Geologic Units	Townships	Sections	Analyses
Big Sagebrush	10*	18	70*	3

*Differences within a category are significant at the 0.05 level; test result among geologic units was performed on a pooled variance estimate.

As with the results given for the native soils, the largest variation for selenium in sagebrush occurred between sections, but to a much greater extent and with the largest disparities from sites in the Cody Shale.

In brief, then, the Cody Shale is the most seleniferous of the geologic units in the Kendrick Project, especially in terms of availability; but it is clearly not uniformly so. The four most selenium-rich sagebrush samples were taken from fairly widespread localities. This precludes narrowing the source in the nonirrigated native rangelands to a specific area.

We found a significant (P=0.05) but low correlation (r=0.34, n=101 pairs) for selenium in soils versus sagebrush. Such poor correlations have been widely reported in

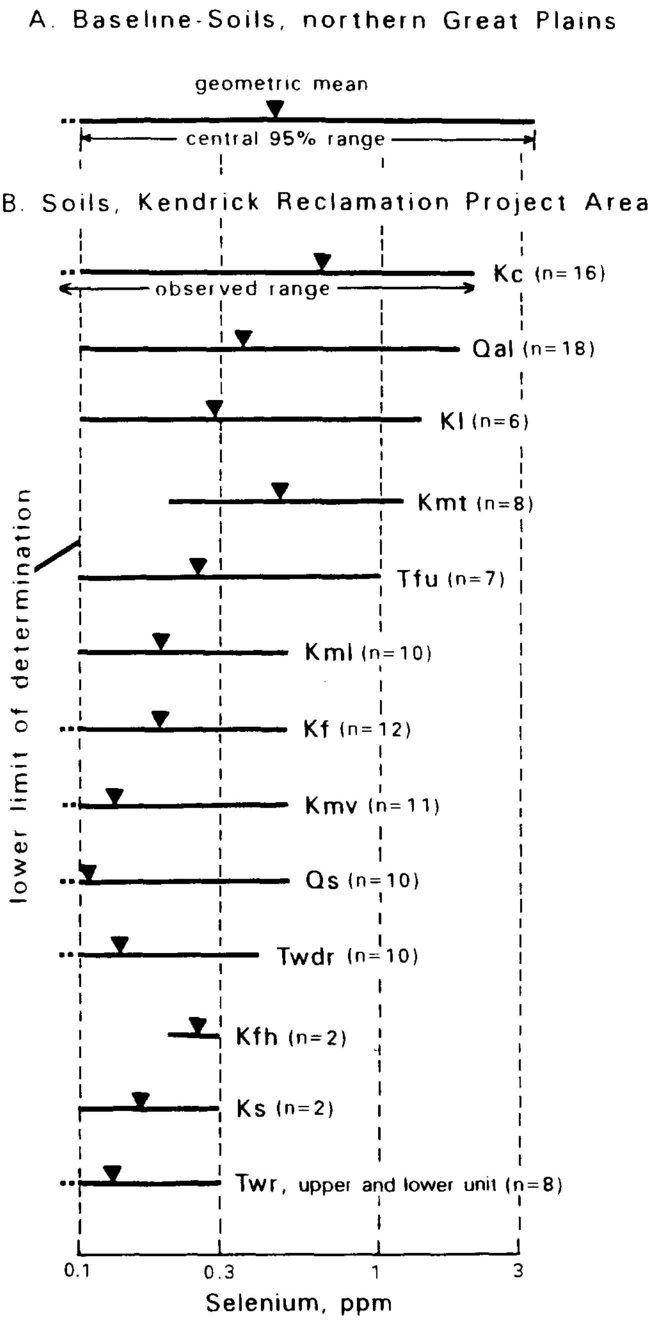

Figure 4. Bar plots of selenium in native soils from geologic units in the Kendrick Reclamation Project Area, arranged in order of decreasing maximum concentrations. Baseline data are from Severson and Tidball (1979). Dashes indicate that the lower end of the range was below the 0.1 ppm lower limit of determination. (See table 1 for explanation of geologic symbols.)

the literature. Olson and others (1942b) found a poor correlation between water-soluble selenium in the surface soil and the selenium content of plants growing in the soil. Still, three of the four sites where sagebrush contained extremely high selenium also had soils with elevated selenium.

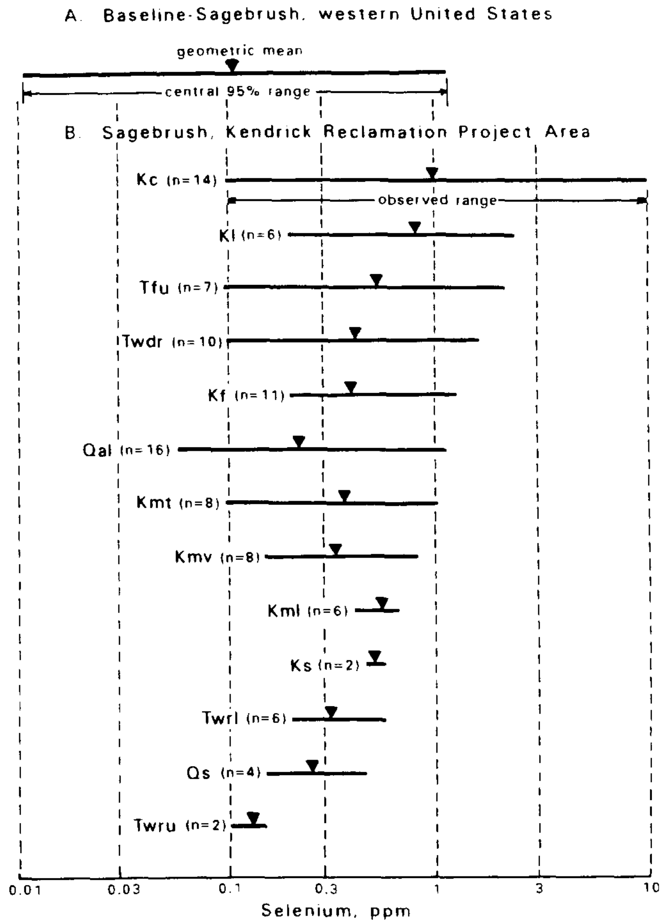

Figure 5. Bar plots of selenium in big sagebrush from geologic units in the Kendrick Reclamation Project Area, arranged in order of decreasing maximum concentrations. Baseline data are from Gough and Erdman (1983). (See table 1 for explanation of geologic symbols.)

Summary statistics for selenium in the native soils and big sagebrush from the various geologic units are given in table 4.

Irrigated Lands

Agricultural Soils

Results of the analysis-of-variance for selenium in agricultural soils, expressed as a percentage of the total variance, are as follows:

	Fields (sections)	Sites	Analyses
Agricultural soils	75*	13	12

*Differences within a category are significant at the 0.05 level.

Table 4. Average and range of selenium concentrations (ppm) in soil and sagebrush determined from stratified random sampling of geologic units at the Kendrick Reclamation Project Area

[Analytical duplicates not included; explanation of geologic units: Qal, Quaternary alluvium; Qs, Quaternary sand dunes; Twr, White River Formation, upper and lower units combined; Twdr, Wind River Formation; Tfu, Fort Union Formation; Kl, Lance Formation; Kfh, Fox Hills Sandstone; Kml, Meeteetse Formation; Kmv, Mesaverde Formation; Kc, Cody Shale; Ks, Steele Shale; Kf, Frontier Formation; Kmt, Mowry and Thermopolis Shales. Detection ratio, number of samples in which the element was found in measurable concentrations relative to the number of samples analyzed]

Geologic unit	Native soil			Sagebrush		
	Detection ratio	Geometric mean	Observed range	Detection ratio	Geometric mean	Observed range
Qal------	18:18	0.35	0.1-1.9	16:16	0.22	0.06-1.2
Qs-------	7:10	.11	<0.1-0.5	4:4	.25	0.15-0.45
Twr------	7:8	.14	<0.1-0.3	8:8	.24	0.1-0.55
Twdr-----	8:10	.14	<0.1-0.4	10:10	.41	0.1-2.0
Tfu------	7:7	.25	0.1-1.0	7:7	.52	0.1-2.2
Kl-------	6:6	.28	0.1-1.4	6:6	.79	0.2-2.2
Kfh------	2:2	.24	0.2-0.3	1:1	.3	0.3-0.3
Kml------	10:10	.19	0.1-0.5	6:6	.53	0.4-0.65
Kmv------	10:11	.13	<0.1-0.5	8:8	.32	0.15-0.8
Kc-------	15:16	.64	<0.1-2.1	14:14	.96	0.1-9.5
Ks-------	2:2	.17	0.1-0.3	2:2	.50	0.45-0.55
Kf-------	11:12	.19	<0.1-0.5	11:11	.39	0.2-1.6
Kmt------	8:8	.47	0.2-1.2	8:8	.36	0.1-1.0

As 75% of the variance can be attributed to differences among irrigated fields, we can contour the concentrations of selenium in soils with reasonable certainty that the map pattern is real. The map contours were computed by averaging the four nearest neighbors and applying an inverse-distance-squared algorithm. Only a small percentage of the variance observed can be attributed to analytical error.

A contour map of selenium in the irrigated soils (fig. 6) shows four areas where peak values exceeded 2 ppm: the southernmost field in the irrigated area (selenium value, 2.2 ppm); Rasmus Lee Lake (a single-point anomaly of 3.6 ppm), Oregon Trail Drain, west of the confluence of Casper Creek with the North Platte River (a single-point anomaly of 3.8 ppm—the maximum observed), and the Johnson Lateral northwest of the Natrona County Airport (a multipoint anomaly with values ranging from 2.2 to 3.2 ppm). We have used 2 ppm as a threshold because soils in North America that are associated with selenosis usually contain 2–6 ppm or more of total selenium (Thornton, 1981, p. 14). Composited soils from only ten of the fields sampled contained selenium in excess of the 2 ppm threshold. As with the results from the native soils in the project area, the concentrations of selenium from the irrigated soils, by themselves, would probably not arouse much interest when compared with the baselines reported for the northern Great Plains (table 3). However, total selenium in soil may not directly reflect irrigation-induced effects, such as increased solubility, transport, and accumulation by an irrigation drainage, nor would it reflect selenium uptake by native and agricultural plants and subsequent utilization by wildlife and livestock.

Alfalfa

Selenium levels in alfalfa ranged from 0.1 to 40 ppm; the median was 0.9 ppm, and 25th and 75th percentiles were 0.4 ppm and 2.0 ppm, respectively. Highly elevated concentrations of selenium in alfalfa were found in three of the four areas identified by the irrigated soil results: Rasmus Lee Lake; near the terminus of the Oregon Trail Drain; and an extensive area underlain by Cody Shale west of the airport (fig. 7) and offset slightly to the south of the seleniferous (>2 ppm) soil area. The extensive area consists of 11 contiguous sections where selenium in alfalfa ranged from 4 to 40 ppm, concentrations that are potentially

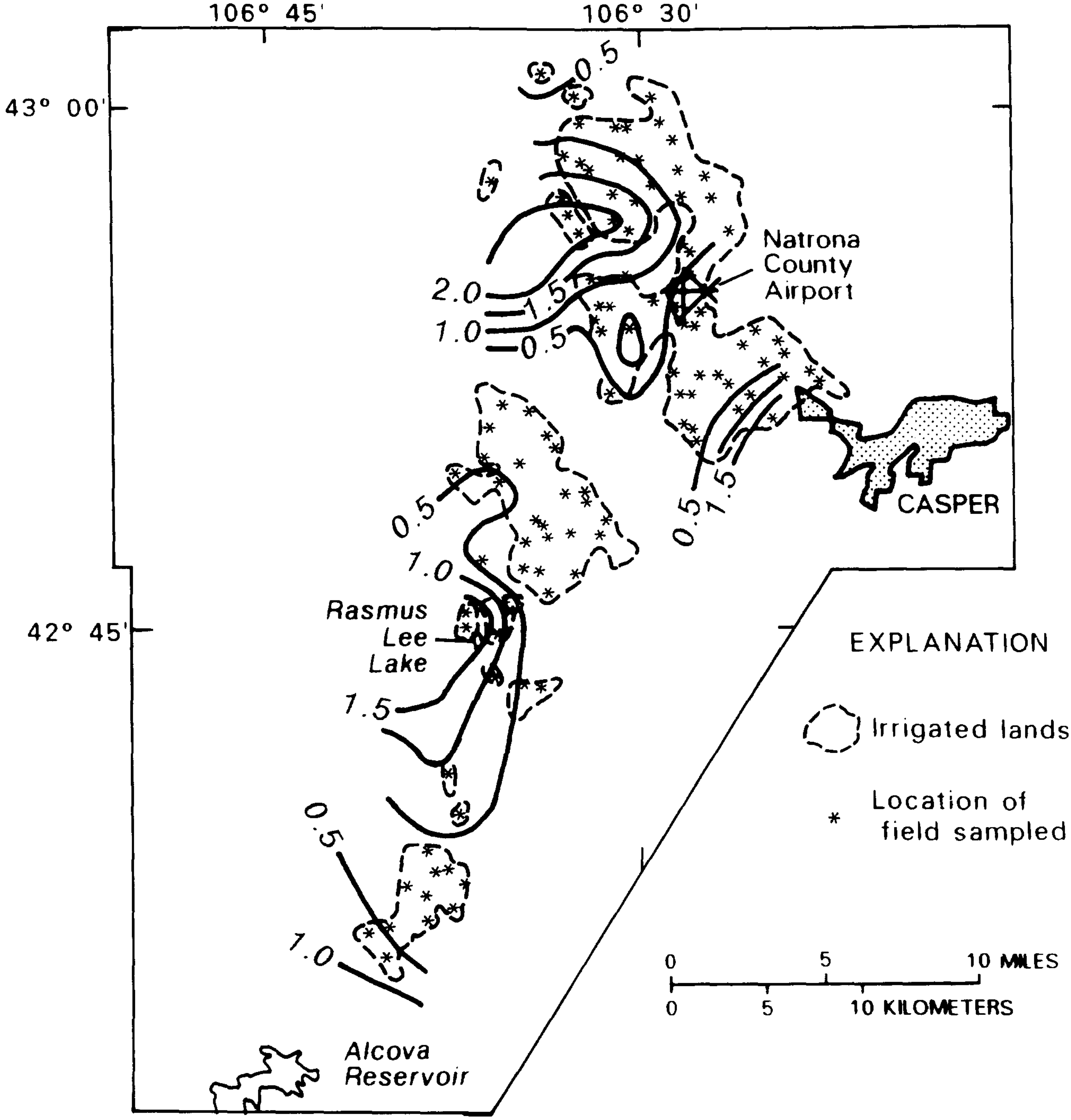

Figure 6. Contour map showing the distribution of total selenium (ppm) in agricultural soils collected from irrigated lands.

hazardous to livestock when consumed over extended periods of time (see Kingsbury, 1964, p. 47; Church and others, 1971, p. 506; Lakin, 1973, p. 96; and Combs and Combs, 1986, p. 26). According to Church and others (1971), alkali disease (manifested by loss of hair and sloughing of hooves) is due to consuming hays and grasses with selenium levels of 10–30 ppm.

The only evidence of selenosis in cattle and horses on the two farms sampled again in 1989 was some hardening of the horses' hoofs. Infrequent incidences of selenosis (alkali disease) have been reported on the Kendrick Project. Tolerance to high selenium levels varies considerably between individual animals. In addition, experimental evidence suggests that some animals may be able to accommodate high levels of dietary selenium after evidencing some symptoms of chronic toxicosis like lameness and hair loss (L.F. James, Poisonous Plant Research Laboratory, United States Department od Agriculture-Agricultural Research Service, oral commun., 1989).

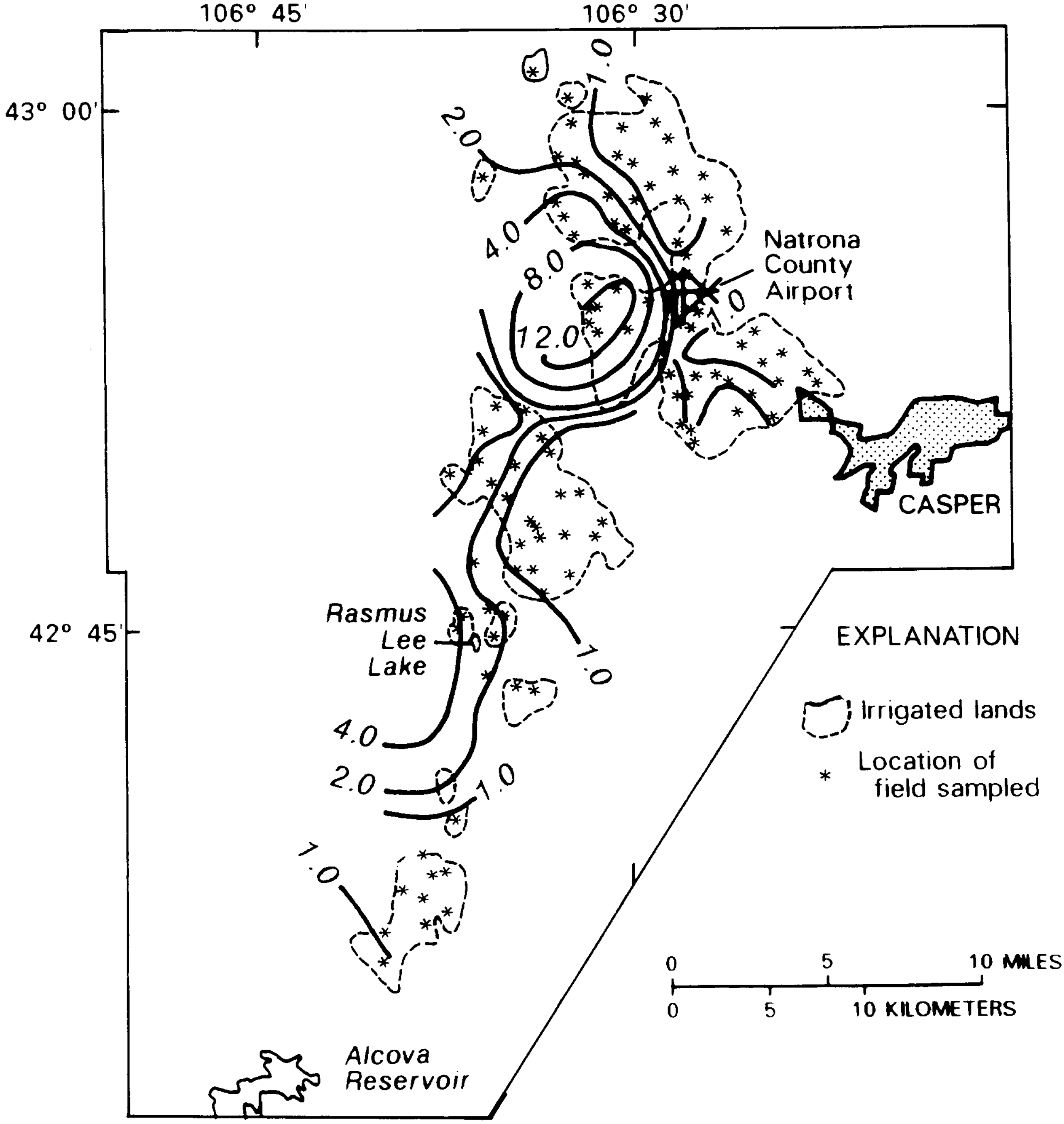

Figure 7. Contour map showing the distribution of selenium (ppm, dry-weight basis) in alfalfa collected from irrigated lands.

The extensive selenium anomaly in alfalfa west of the airport was independently confirmed by water-quality data provided by David Naftz and his associates with the Water Resources Division of the United States Geological Survey. Dissolved selenium concentrations ranged from 0.12 to 0.98 mg/L in drain-water samples and from 1.7 to 5.3 mg/L in ponded-water samples. These concentrations exceed the 0.100 mg Se/L guideline for irrigation water used in the production of alfalfa (Albasel and others, 1989). Drinking water and domestic-livestock water standards are 0.01 mg/L and 0.05 mg/L, respectively (U.S. Environmental Protection Agency, 1977).

Clearly, some of the alfalfa produced in the Kendrick area contains selenium above most reported concentrations. It is difficult to assess the importance of the high values because most published studies on selenium in alfalfa are from selenium-deficient or nonseleniferous regions (Ihnat and Wolf, 1989). Several exceptions include an early study by Byers and others (1938) that reports a maximum concentration of 7 ppm selenium in alfalfa from southeastern Colorado. A second exception is a report of up to 44 ppm selenium in alfalfa grown in Israel (Ravikovitch and Margolin, 1957). We also have a record (Oscar Olson, South Dakota State University, written commun., 1975) of an alfalfa sample that contained 27.3 ppm selenium. Concentrations of 12 and 13 ppm were found in two samples of alfalfa collected from Wallace Meadows northeast of Lusk, Wyoming (by H.F. Mayland, unpubl. data, 1989).

On the other hand, we found alfalfa from eight fields that is marginally deficient (0.10–0.20 ppm) in selenium. According to Allaway and Hodgson (1964), Westermann and Robbins (1974), and Fisher and others (1987), minimal dietary selenium concentrations—critical levels needed to prevent white muscle disease (a form of muscular dystrophy) in livestock—are about 0.1 ppm. Alfalfa that contained selenium below 0.5 ppm generally came from fields in the southern half of the Kendrick Project.

Results of the analysis-of-variance simply confirm the strong differences among fields shown in figure 7 and also reflected in the soils, although not quite so strongly. The distribution of the variance, expressed as a percentage of the total variance, follows:

	Fields (sections)	Sites	Analyses
Alfalfa	60	39*	<1

*Differences within a category are significant at the 0.05 level.

Our results from the Rasmus Lee Lake area provide an example of the extreme differences observed among fields. The composite alfalfa sample from a pasture just northwest of the lake contained 15 ppm selenium; whereas, a sample from a heavily irrigated hay field to the east contained only 0.25 ppm.

Of nine bottom-sediment samples collected from the Kendrick area during an earlier field-screening study (Severson and others, 1987b), the sediment from Rasmus Lee Lake contained 17 ppm, second only to a sample from the mouth of Poison Spring Creek that contained 25 ppm. Recent unpublished results of pore-space analyses (David Naftz, oral commun., April 1989) showed 30 mg/L dissolved selenium in a sample of pore water 15 feet below land surface in a sand lens near the field where the alfalfa contained 15 ppm selenium. In marked contrast, a pore-water sample contained only 0.150 mg Se/L from the field in which the alfalfa sample contained 0.25 ppm. Alfalfa, a deep-rooted plant, seems to provide a good indirect measure of soluble selenium in the pore spaces at depth. As Fisher and others (1987, p. 124) stressed: "the ability of selenium-accumulating plants to absorb selenium from sources deep within the soil profile indicate that surface soil elemental analyses have serious limitations as a means of forecasting toxicity problems."

Unlike the results for selenium in the agricultural soils, we found strong differences in selenium from alfalfa taken within the same field. The largest disparity occurred between the two sites from a field where the sample from the first site contained only 0.85 ppm selenium; whereas, the sample from the second site contained 7.0 ppm. These results, although disturbing, simply support those reported by Olson and others (1942b) who also found large variations in the selenium content of plants over relatively short distances on soils derived from the same parent material. Differences between site pairs from the other six fields where such comparisons can be made were considerably less extreme.

Results of a correlation analysis that compared total selenium in the agricultural soils with selenium in alfalfa from the same fields were similar to those found between native soils and sagebrush. The correlation coefficient in this case was 0.43 (n=105 pairs); although the correlation is significant (P=0.05), the soil selenium explains only about 16% of that found in the alfalfa.

The offset or displacement of a large zone of seleniferous alfalfa and selenium-laden surface waters from a possible source area of slightly seleniferous soils to the north is difficult to explain. Almost 50 years ago, however, Olson, Whitehead, and Moxon (1942) seemed to have dealt with similar patterns. They concluded (p. 52):

> During the weathering of seleniferous rock to soil in the region in which these studies were made, a large part of the selenium is oxidized to the selenate form. As the selenate, it is leached from the surface to subsurface soils or *removed by run-off waters and redeposited at lower elevations*, where it may finally leach from the surface and be deposited in subsurface soil. [emphasis added.]

Much more recently, Tidball and others (1989b) reported what appears to be a very similar situation in an irrigated area of the San Joaquin Valley, California. Elevated levels of selenium in soils have been dispersed downslope toward areas where the water table is close to the surface and where the groundwater is extremely seleniferous. At present this displacement seems to be the only explanation for the major selenium anomaly at Kendrick.

Selenium concentrations in the alfalfa samples collected from the two fields in June 1989 were less than 5% of the concentrations found in alfalfa sampled from the same fields in June 1988. In the field where the 1988 sample contained 25 ppm selenium, the three 1989 samples contained only 0.2 ppm; whereas, in the field where the 1988 sample contained 15 ppm, the single 1989 composite sample had 0.7 ppm. Differences in selenium concentrations owing to drying methods were not significant at the 0.05