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A Review and Analysis of  
Parameters for Assessing Transport  
of Environmentally Released  
Radionuclides through Agriculture

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Section 2

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## 2. ELEMENT-SPECIFIC TRANSPORT PARAMETERS

Quantification of nuclide transport through agricultural systems in TERRA involves the parameters describing soil-to-plant uptake for vegetative growth (leaves and stems),  $B_v$ ; and nonvegetative growth (fruits, seeds, and tubers),  $B_r$ ; ingestion-to-milk transfer,  $F_m$ ; ingestion-to-meat transfer for beef cattle,  $F_f$ ; and the soil-water distribution coefficient,  $K_d$ . Ideally, these transport parameters should be nuclide-specific. For example, isotopic differences in plant availability have been shown for plutonium.<sup>8-10</sup> However, available information for other elements and the lack of compelling theory for a nuclide-specific approach necessitates an element-specific determination for these parameters. Thus, it is assumed here that variability among isotopes of the same element is insignificant compared to variability among different elements and the overall variability inherent in the parameters themselves. For soil-plant uptake of strontium, available information supports this assumption.<sup>11</sup>

### 2.1 Soil-to-Plant Uptake Parameters $B_v$ and $B_r$

Root uptake of radionuclides incorporated into surface horizons of soil is parameterized by the transfer coefficients  $B_v$  and  $B_r$ , representing the ratio of elemental concentrations in plant and soil at harvestable maturity. The parameters  $B_v$  and  $B_r$  are given by

$$B_v = \frac{C_v}{C_s} \text{ and} \quad (1)$$

$$B_r = \frac{C_r}{C_s} \quad (2)$$

where

- $B_v$  = soil-to-plant elemental transfer coefficient for vegetative portions of food crops and feed plants,
- $B_r$  = soil-to-plant elemental transfer coefficient for nonvegetative (reproductive) portions of food crops and feed plants,
- $C_v$  = elemental concentration in vegetative portions of food crops and feed plants (dry weight) at edible maturity,
- $C_r$  = elemental concentration in nonvegetative (reproductive) portions of food crops and feed plants (dry weight) at edible maturity, and
- $C_s$  = elemental concentration in root zone soil (dry weight).

This approach to concentration ratios is significantly different from the  $B_{iv1}$  and  $B_{iv2}$  approach used by Moore et al.<sup>1</sup> and is in response to some inconsistencies and inadequacies experienced with the AIRDOS-EPA approach.<sup>12</sup> In Moore et al.,<sup>1</sup>  $B_{iv1}$  values were calculated from dry plant/dry soil concentration ratios for livestock feeds, and  $B_{iv2}$  values were calculated from fresh weight plant/dry soil concentration ratios for food crops. This approach was used because information on feed and food crops is customarily reported in dry and fresh weights, respectively. In analysis of available literature for these concentration ratios, all data in a reference were divided into "animal feeds" and "direct consumption by man" categories, corresponding to  $B_{iv1}$  and  $B_{iv2}$ , respectively. A literature reference could be used for  $B_{iv1}$  or  $B_{iv2}$  or both. Conversely,  $B_{iv1}$  and  $B_{iv2}$  for an element might be derived from two sets of data and references which could be equal, share common elements, or be disjointed. For most elements,  $B_{iv2} \leq B_{iv1}$  was observed. This result is logical because the concentration of a finite quantity of material in a plant decreases as plant weight increases. However, if two disjointed sets of references were used,  $B_{iv2} \geq B_{iv1}$  for an element could occur. The resultant

values of  $B_{iv1}$  and  $B_{iv2}$  were appropriate with respect to the references used to generate them, but were not directly comparable with each other. In the approach used here, classification of references is based on physiologic plant characteristics, and not upon ultimate fate of the plant in the human food chain.

Also, in the Moore et al.<sup>1</sup> approach, any statistical analysis of  $B_{iv2}$  would have to be based on “converted” parameter values because they are usually reported in dry weight. Because very few references include dry-to-wet weight conversion factors, general references such as Morrison (1959)<sup>13</sup> and Spector (1959)<sup>14</sup> were used for generation of  $B_{iv2}$ . In some cases a value of 25% dry matter<sup>1,6,15</sup> was used to convert to wet weight. These transformations of reported data added unnecessary uncertainty to parameter estimates, and statistical analysis would be less precise than analysis of original data. Thus, the adoption of dry weight concentration ratios here reduces additional imprecision in parameter estimates and facilitates a more direct comparison between the two concentration factors ( $B_v$  and  $B_r$ ).

Adoption of  $B_v$  and  $B_r$  over  $B_{iv1}$  and  $B_{iv2}$  is based on an evaluation of literature references for root uptake and distribution of elements in plants. Nonuniform elemental distributions in food and feed crops has been widely observed (Table 2.1). Typically, nonnutritional elemental concentrations in agricultural plants are generally ordered as roots > leaves  $\geq$  stems > tubers  $\geq$  fruits  $\geq$  seeds.<sup>10,17,31-37</sup> Variations in the relative distribution of elements among plant parts occur with species, variety, growth conditions, and element, but in general for most elements,  $C_v > C_r$ .

Analysis of food and feed production in the conterminous United States suggests that  $B_v$  and  $B_r$  are analogous to  $B_{iv1}$  and  $B_{iv2}$ , respectively. Leafy vegetables are the only group of food crops for which  $B_v$  is the appropriate transfer parameter. Nationally, leafy vegetables comprise a relatively small portion of food crop production (Table 2.2). Thus, major portions of food crops in the United States are associated with the transport parameter  $B_r$ . For feed crops, grains are the only category associated with  $B_r$ . Although the relative importance of grain feeds varies considerably by state and county, in most areas nongrain feeds dominate. Therefore, the use of default soil-to-plant transport parameters (reviewed in the following sections) in the computer code AIRDOS-EPA merely requires substitution of  $B_v$  for  $B_{iv1}$  and substitution of a  $B_r$ , converted from dry weight to wet weight, for  $B_{iv2}$ . Appropriate generic factors for conversion of  $B_r$  to  $B_{iv2}$ , based on relative importance of various nonleafy vegetables in the United States, are 0.126, 0.222, and 0.888 for exposed produce, protected produce, and grains, respectively (Table 2.3). Weighting these conversion factors by the relative importance (based on production in kilograms) of each category in the United States (Table 2.2) yields an overall average value of 0.428. However, regional differences in the relative importance of the food categories and assessment requirements may require the selection of more appropriate conversion factors from Tables 2.2 and 2.3.

### 2.1.1 Protocols for determination of parameter values

All estimates of  $B_v$  and  $B_r$  are based on any combination of 1) analysis of literature references, 2) correlations with other parameters, 3) elemental systematics, or 4) comparisons of observed and predicted elemental concentrations in foods. In general, no *a priori* biases or protocols were used to produce conservative values.

Analysis of literature references required subjective evaluation of the experimental techniques, reliability of reported data, and appropriateness of reported values to the parameters. Practically, when many references were available for an element, subjective standards were relatively high; when only one or a few references were available, standards were less rigorous, and alternative approaches became increasingly important. Occasionally, reported data was not amenable for direct calculation of  $B_v$  or  $B_r$  based on Eqs. (1) and (2). If such corollary information such as soil bulk density, crop yield, background concentration, counting efficiency, and specific activities were not reported or easily available from other references, estimates of them were made for indirect

**Table 2.1. Examples of nonuniform elemental distribution in plants**

Element	$(C_r/C_v)^a$	Plant	Reference
Li	$1.6 \times 10^{-1}$	pumpkin	16
Be	$1.4 \times 10^{-1}$	pumpkin	16
B	$3.1 \times 10^{-1}$	various vegetables	17
Na	$6.8 \times 10^{-1}$	pumpkin	16
Mg	$6.6 \times 10^{-1}$	grain and root crops	18
Ca	$1.6 \times 10^{-1}$	grain and root crops	18
Ti	$5.3 \times 10^{-1}$	sedge and nut grasses	19
Cr	$5.7 \times 10^{-1}$	pumpkin	16
Mn	$2.0 \times 10^{-1}$	various vegetables	17
Fe	$1.1 \times 10^{-1}$	pumpkin	16
Co	$2.7 \times 10^{-1}$	sedge and nut grasses	19
Zn	$3.5 \times 10^{-1}$	corn	20
Sr	$8.7 \times 10^{-2}$	oats	21
Y	$1.3 \times 10^{-1}$	beans	22
Mo	$1.2 \times 10^{-1}$	various vegetables	17
Tc	$1.9 \times 10^{-2}$	wheat	23
Cd	$7.0 \times 10^{-2}$	various vegetables	24
I	$4.9 \times 10^{-1}$	various vegetables	25
Cs	$2.6 \times 10^{-1}$	wheat	26
Ba	$9.6 \times 10^{-2}$	pumpkin	16
Ce	$3.4 \times 10^{-1}$	beans	22
Pb	$4.2 \times 10^{-2}$	various vegetables	27
Po	$1.5 \times 10^{-1}$	various vegetables	28
U	$5.0 \times 10^{-1}$	various grain and root crops	29
Np	$3.5 \times 10^{-2}$	wheat	30
Pu	$1.2 \times 10^{-2}$	various vegetables	10
Am	$4.2 \times 10^{-3}$	various vegetables	10
Cm	$6.7 \times 10^{-3}$	various vegetables	10

<sup>a</sup> $(C_r/C_v)$  ratios were determined when pairs of observations were reported for a plant type. values in the table are the geometric mean of these ratios for the given reference.

calculation of  $B_v$  or  $B_r$ . Acceptance or rejection of such references was subjective, depending on the number and quality of other available references and comparison of indirect estimates with direct estimates from reliable sources. Often reported data were presented graphically. When such references were used, some error from visual interpretation of the graphs is inherent in resultant parameter estimates.

Although past estimates of plant uptake parameters have been based on the assumption of equilibrium,<sup>39,40</sup> studies in which the concentration of polonium,<sup>41</sup> radium,<sup>42</sup> cesium,<sup>43</sup> a mixture of fission products,<sup>44</sup> or strontium<sup>43,45-51</sup> in assorted plants has been repeatedly measured indicate that concentration factors for radionuclides change with time. If equilibrium or near-equilibrium conditions are achieved, they occur late in plant ontogeny. Because the transport parameters are used to generate plant concentrations at edible maturity for all vegetative categories, except pasture, an attempt was made to use references in which plant and soil concentrations were measured at edible maturity of the plant. In a majority of references, soil concentrations are given for the beginning of the experiment and plant concentrations are usually measured several weeks or months later. Because for most elements concentration factors are small and removal mechanisms from soil are controlled, only slight error is introduced in using such references. Also, concentration factors determined before edible maturity were used if subjective evaluation of the experiment suggested only slight error would be introduced from using these references. However, most references in which concentration factors were measured within three weeks of seed germination were rejected. For experimental determination of concentration factors for technetium, the above considerations severely limited the available data base.

**Table 2.2. Relative importance of food crop categories in selected states and the conterminous U.S.<sup>a</sup>**

	Percent of total			
	Leafy vegetables	Exposed produces	Protected produce	Grains
California				
Area harvested	8.1	32.7	42.6	16.5
Production	14.4	52.3	29.7	3.5
Florida				
Area harvested	2.8	6.8	87.0	3.5
Production	4.9	7.2	87.4	0.6
Maine				
Area harvested	0.1	14.9	83.1	2.0
Production	0.1	3.1	96.6	0.2
Minnesota				
Area harvested	<0.1	0.4	25.2	74.3
Production	0.2	1.3	46.6	51.9
Montana				
Area harvested	<0.1	<0.1	4.1	95.9
Production	<0.1	0.1	12.0	87.9
Texas				
Area harvested	1.4	1.8	33.1	63.7
Production	10.3	5.2	55.1	29.4
Virginia				
Area harvested	1.5	14.6	32.1	51.8
Production	4.7	31.7	34.9	28.6
Conterminous U.S.				
Area harvested	1.2	6.1	23.3	69.4
Production	5.8	20.0	42.2	32.0

<sup>a</sup>Reference: Shor, Baes, and Sharp<sup>7</sup>, Appendix B.

If a reference was judged appropriate, analysis of the reported values was done in a manner similar to that of Moore et al.<sup>1</sup> with several modifications. First, all reported values were divided into those for vegetative growth (leaves, stems, straws) or nonvegetative growth (reproductive and storage parts such as fruits, seeds, and tubers). Plant concentrations for the former were used in calculation of  $B_v$  and the latter for  $B_r$ . Also, if  $C_v$  and  $C_r$  were reported for a single plant type (e.g., wheat straw and grain or carrot top and root), the ratio ( $C_r/C_v$ ) was calculated. The geometric mean of all reported values applied to  $B_v$ ,  $B_r$ , or ( $C_r/C_v$ ) ratio was calculated for each reference. For some references the ( $C_r/C_v$ ) ratio could be calculated, but  $B_v$ , and  $B_r$  could not because hydroponic solutions were used to grow plants or  $C_s$  was not reported. Finally, the geometric means for each reference were used to construct a distribution for  $B_v$ ,  $B_r$ , or ( $C_r/C_v$ ) ratio. The geometric means of these (inter-reference) distributions were taken to be the best unbiased estimates of the parameters, because reported values often spanned more than an order of magnitude, and because the distributions for elements strontium, cesium, and plutonium (for which there were numerous references) appeared to be lognormally distributed.

**Table 2.3. Dry-to-wet weight conversion factors for exposed produce, protected produce, and grains**

Vegetable	Conversion factor <sup>a</sup>	Weighting factor <sup>b</sup>	Reference	Vegetable	Conversion factor	Weighting factor	Reference
Exposed produce				Protected produce			
Apple	0.159	15.4	14	Onion	0.125	3.6	14
Asparagus	0.070	0.6	14	Orange	0.128	22.8	14
Bushberries	0.151	1.6	14	Peanut	0.920	3.4	38
Cherry	0.170	0.7	14	Peas	0.257	0.4	14
Cucumber	0.039	4.0	14	Potato	0.222	33.7	14
Eggplant	0.073	0.1	14	Sugarbeet	0.164	6.5	13
Grape	0.181	20.2	14	Sugarcane	0.232	5.5	13
Peach	0.131	6.9	14	Sweet corn	0.261	6.0	14
Pear	0.173	3.5	14	Sweet potato	0.315	1.5	14
Plums and prunes	0.540	3.1	14	Tree nuts	0.967	0.4	14
Sweet pepper	0.074	1.3	14	Watermelon	0.079	2.6	14
Snap bean	0.111	0.7	14				
Squash	0.082	1.8	14	Weighted average	0.222		
Strawberry	0.101	1.3	14				
Tomato	0.059	38.8	14	Grains			
				Barley	0.889	10.1	14
Weighted average	0.126			Corn (for meal)	0.895	37.7	38
Protected produce				Oats	0.917	2.3	14
Bean (dry)	0.878	2.2	14	Rye	0.890	0.5	14
Cantaloupe	0.060	1.1	14	Soybean	0.925	5.3	14
Carrot	0.118	2.4	14	Wheat	0.875	44.0	14
Grapefruit	0.112	5.5	14				
Lemon	0.107	2.4	14	Weighted average	0.888		

<sup>a</sup>Conversion factor = grams dry/grams wet.

<sup>b</sup>Relative importance based on production in kilograms (percent of total) in the United States based on reference 7.

When only a few literature references were available, alternatives or supplements to the geometric means of distributions method were employed. For example, it was found that  $B_v$  was correlated with  $C_s$  for several elements, e.g., B, P, Cu, and Zn. That is, entry of the element into the plant appeared to be regulated rather than a constant fraction of the soil concentration. Therefore, studies employing highly enriched soil concentrations might yield inappropriate concentration factors for model calculations. Such correlations were combined with average or typical observed soil concentrations<sup>52</sup> to generate appropriate concentration factors.

Another approach to determination of concentration factors was to compare plant concentrations surveyed in the literature<sup>53,54</sup> with those generated by the equations

$$C_v = B_v C_s^t \text{ and} \quad (3)$$

$$C_r = B_r C_s^t, \quad (4)$$

where  $C_s^t$  is an average or typical soil concentration reported in the literature.<sup>52</sup> If predicted plant concentrations were clearly atypical of reported values, the concentration factors were revised accordingly. In general, this method served as a critique of, or supplement to, other methods because of the uncertainties in values for “average” soil and plant concentrations. Typically, these values ranged over two orders of magnitude.

Finally, for rare elements and elements with little or no experimental information available, elemental systematics were used to derive best estimates when no other method or information was available. That is, relationships established between concentration factors for an element and those for other elements of the same or adjacent periods or groups were examined for trends. Such trends were extrapolated to the element in question, with the implication that chemically similar elements act similarly in the soil-plant environment. This elemental analog approach was extremely useful when support information for  $B_r$  was unavailable or meager. Systematic trends in observed ( $C_r/C_v$ ) ratios were often used to predict  $B_r$  from  $B_v$  when the support data for the former was lacking, but relatively good for the latter.

Selection of values used as default in the TERRA code involved all of the above procedures. The final value selected as default was estimated to two significant digits rounded off to the nearest 0.5 decimal place (Figs. 2.1 and 2.2). That is, if a value of 1.3 was determined from the various above-outlined procedures a value of 1.5 was adopted. A determined value of 1.2 was rounded off to 1.0. The values of  $B_v$  and  $B_r$  in Figures 2.1 and 2.2 are further discussed in the following sections (2.1.2 through 2.1.10).

### 2.1.2 Group IA and IIA elements

The Group IA or alkali metals (Li, Na, K, Rb, Cs, and Fr) and the Group IIA or alkaline earth metals (Be, Mg, Ca, Sr, Ba, and Ra) are, generally, relatively easily taken up from soil by plants. Many of the lighter of these elements are essential plant nutrients and some, including isotopes of cesium, strontium, and radium, are extremely important radiologically. Literature references for calculation of  $B_v$  and  $B_r$  for cesium<sup>26,34,55-71</sup> and strontium<sup>11,16-19,21,31-33,59-86</sup> are quite abundant. Available references for the rest of the elements in these two groups are less numerous. References were available for lithium,<sup>16</sup> sodium,<sup>16,17,65</sup> potassium,<sup>16-18,65,71,84</sup> rubidium,<sup>65</sup> beryllium,<sup>16</sup> magnesium,<sup>16,18,65,71</sup> calcium,<sup>16,18,65,71,72,84,85</sup> and radium.<sup>87-93</sup> No references were found for francium.

Cesium is the best documented of the Group IA elements. Analysis of the 18 references from which  $B_v$  estimates were taken suggests that the distribution of geometric means is lognormal (Fig. 2.3). The geometric means established for each of the 18 references ranged from 0.018 to 0.52 with a geometric mean of the means = 0.078. This value was rounded off to 0.08 for use in TERRA. Half of the  $B_v$  references included information pertinent to  $B_r$ , yielding a geometric mean of 0.018 for  $B_r$ . Ten of the references yielded ( $C_r/C_v$ ) ratios, suggesting a value of 0.49 for this ratio. Using this ratio value with the  $B_r$  estimate previously mentioned yields a second estimate of  $B_r$  of 0.038 by the equation

$$B_r = B_v \left[ \frac{C_r}{C_v} \right] \quad (5)$$

Thus, an estimate of  $B_r = 0.03$ , which is near the midpoint of the range (0.018 to 0.038), was adopted. The ratio of default values of  $B_r$  and  $B_v$  ( $B_r/B_v$ ) is within one standard deviation of the ( $C_r/C_v$ ) ratio distribution determined from the 10 references. Comparison of observed concentrations of cesium in plant foods with those predicted using the default estimate for  $B_r$  (Fig. 2.2) suggests that the default value is not unreasonable (Table 2.4). No information on naturally occurring cesium in vegetation applicable to  $B_v$  was available, but a radiological survey of the Marshall Islands<sup>94</sup> indicates that predicted Cs-137 concentrations in plants using the default estimate of  $B_v$  and measured soil concentrations are less than observed concentrations (which include resuspended material).

The  $B_v$  and  $B_r$  values chosen for lithium are derived from an unpublished study by Baes and Katz of natural variations in elemental concentrations in associated pumpkins and soils.<sup>16</sup>

	I A	II A											III A	IV A	V A	VI A	VII A
II	Li 0.025	Be 0.010											B 4.0		N 30		F 0.060
III	Na 0.075	Mg 1.0	III B	IV B	V B	VI B	VII B	VIII		I B	II B	Al $4.0 \times 10^{-3}$	Si 0.35	P 3.5	S 1.5	Cl 70	
IV	K 1.0	Ca 3.5	Sc $6.0 \times 10^{-3}$	Ti $5.5 \times 10^{-3}$	V $5.5 \times 10^{-3}$	Cr $7.5 \times 10^{-3}$	Mn 0.25	Fe $4.0 \times 10^{-3}$	Co 0.020	Ni 0.060	Cu 0.40	Zn 1.5	Ga $4.0 \times 10^{-3}$	Ge 0.40	As 0.040	Se 0.025	Br 1.5
V	Rb 0.15	Sr 2.5	Y 0.015	Zr $2.0 \times 10^{-3}$	Nb 0.020	Mo 0.25	Tc 9.5	Ru 0.075	Rh 0.15	Pd 0.15	Ag 0.40	Cd 0.55	In $4.0 \times 10^{-3}$	Sn 0.030	Sb 0.20	Te 0.025	I 0.15
VI	Cs 0.080	Ba 0.15		Hf $3.5 \times 10^{-3}$	Ta 0.010	W 0.045	Re 1.5	Os 0.015	Ir 0.055	Pt 0.095	Au 0.40	Hg 0.90	Tl $4.0 \times 10^{-3}$	Pb 0.045	Bi 0.035	Po $2.5 \times 10^{-3}$	At 1.0
VII	Fr 0.030	Ra 0.015															
Lanthanides	La 0.010	Ce 0.010	Pr 0.010	Nd 0.010	Pm 0.010	Sm 0.010	Eu 0.010	Gd 0.010	Tb 0.010	Dy 0.010	Ho 0.010	Er 0.010	Tm 0.010	Yb 0.010	Lu 0.010		
Actinides	Ac $3.5 \times 10^{-3}$	Th $8.5 \times 10^{-4}$	Pa $2.5 \times 10^{-3}$	U $8.5 \times 10^{-3}$	Np 0.10	Pu $4.5 \times 10^{-4}$	Am $5.5 \times 10^{-3}$	Cm $8.5 \times 10^{-4}$									
Key:	Li 0.025	— Symbol		— Transfer Coefficient, $B_v$													

Figure 2.1. Values of the soil-to-plant concentration factor  $B_v$ , adopted as default estimates in the computer code TERRA.



	I A	II A											III A	IV A	V A	VI A	VII A
II	Li $4.0 \times 10^{-3}$	Be $1.5 \times 10^{-3}$											B 2.0		N 30		F $6.0 \times 10^{-3}$
III	Na 0.055	Mg 0.55	III B	IV B	V B	VI B	VII B	VIII		IB	II B	Al $6.5 \times 10^{-4}$	Si 0.070	P 3.5	S 1.5	Cl 70	
IV	K 0.55	Ca 0.35	Sc $1.0 \times 10^{-3}$	Ti $3.0 \times 10^{-3}$	V $3.0 \times 10^{-3}$	Cr $4.5 \times 10^{-3}$	Mn 0.050	Fe $1.0 \times 10^{-3}$	Co $7.0 \times 10^{-3}$	Ni 0.060	Cu 0.25	Zn 0.90	Ga $4.0 \times 10^{-4}$	Ge 0.080	As $6.0 \times 10^{-3}$	Se 0.025	Br 1.5
V	Rb 0.070	Sr 0.25	Y $6.0 \times 10^{-3}$	Zr $5.0 \times 10^{-4}$	Nb $5.0 \times 10^{-3}$	Mo 0.060	Tc 1.5	Ru 0.020	Rh 0.040	Pd 0.040	Ag 0.10	Cd 0.15	In $4.0 \times 10^{-4}$	Sn $6.0 \times 10^{-3}$	Sb 0.030	Te $4.0 \times 10^{-3}$	I 0.050
VI	Cs 0.030	Ba 0.015		Hf $8.5 \times 10^{-4}$	Ta $2.5 \times 10^{-3}$	W 0.010	Re 0.35	Os $3.5 \times 10^{-3}$	Ir 0.015	Pt 0.025	Au 0.10	Hg 0.20	Tl $4.0 \times 10^{-4}$	Pb $9.0 \times 10^{-3}$	Bi $5.0 \times 10^{-3}$	Po $4.0 \times 10^{-4}$	At 0.15
VII	Fr 0.030	Ra 0.015															

Lanthanides	La $4.0 \times 10^{-3}$	Ce $4.0 \times 10^{-3}$	Pr $4.0 \times 10^{-3}$	Nd $4.0 \times 10^{-3}$	Pm $4.0 \times 10^{-3}$	Sm $4.0 \times 10^{-3}$	Eu $4.0 \times 10^{-3}$	Gd $4.0 \times 10^{-3}$	Tb $4.0 \times 10^{-3}$	Dy $4.0 \times 10^{-3}$	Ho $4.0 \times 10^{-3}$	Er $4.0 \times 10^{-3}$	Tm $4.0 \times 10^{-3}$	Yb $4.0 \times 10^{-3}$	Lu $4.0 \times 10^{-3}$
Actinides	Ac $3.5 \times 10^{-4}$	Th $8.5 \times 10^{-5}$	Pa $2.5 \times 10^{-4}$	U $4.0 \times 10^{-3}$	Np 0.010	Pu $4.5 \times 10^{-5}$	Am $2.5 \times 10^{-4}$	Cm $1.5 \times 10^{-5}$							

Key: 

Li	—	Symbol
$4.0 \times 10^{-3}$	—	Transfer Coefficient, $B_f$

Figure 2.2. Values of the soil-to-plant concentration factor  $B_f$ , adopted as default estimates in the computer code TERRA.

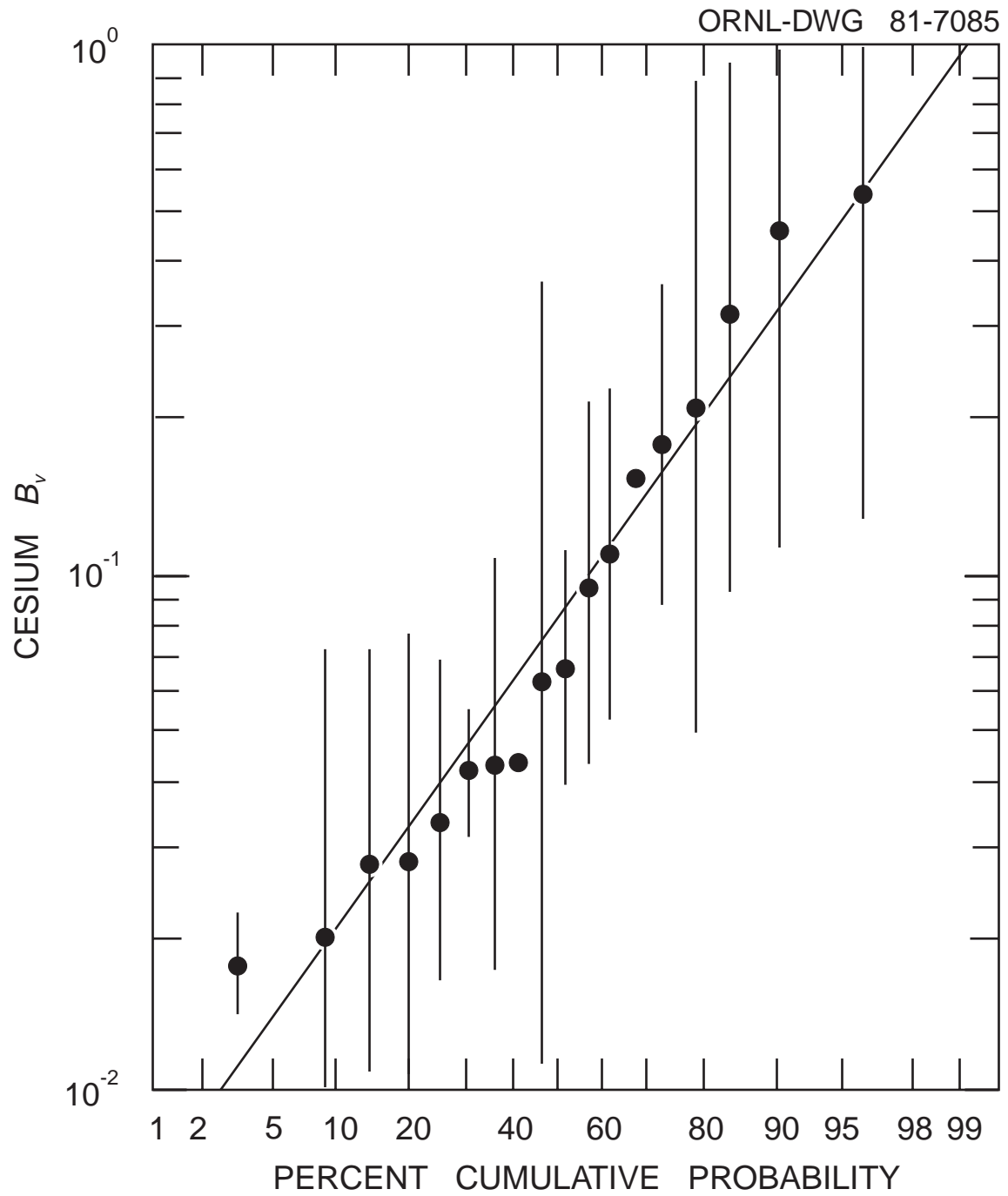


Figure 2.3. Lognormal probability plot of geometric means of  $B_v$  for cesium (calculated from references 26, 34, and 55-71), including one geometric standard deviation of the mean.

Comparison of observed and predicted plant concentrations in Table 2.4 indicates that both default  $B_v$  and  $B_r$  predict plant concentrations which are within observed ranges.

The  $B_v$  for sodium (0.075) was also derived from reference 16. Reference 65 reported soil and plant concentrations from which a lower estimate of  $B_v$  for sodium was derived, but systematic trends observed by plotting  $B_v$  against atomic number for Group IA and IIA elements (Fig. 2.4). suggest the rejection of this lower value. Comparison of observed and predicted plant sodium using the higher value supports its selection, because the predicted value is slightly below the reported range.

An estimate of the  $(C_r/C_v)$  ratio for sodium of 0.74 was derived from references 16 and 17. One and two standard deviations of the data reported in references 17 and 16, respectively, include the value 1.0. Thus,  $B_v = B_r$  for sodium is quite likely for many plants. However, reported values of  $C_r$  for sodium are generally less than  $C_v$ . Thus, the derived ratio of 0.74 was judged acceptable, yielding a default value of 0.055 for sodium  $B_r$  using Eq. (5). This estimate of  $B_r$  appears reasonable (Table 2.4).

The default value of  $B_v$  for potassium was determined to be 1.0. This value is based on the geometric mean of values determined for two references (16 and 65), the correlation between  $B_v$  and  $C_s$  for potassium observed from these references (Fig. 2.5), and the assumption that typical agricultural practice includes soil fertilization with potassium.

The  $(C_r/C_v)$  ratio based on literature references is quite variable for potassium. Values at or near 1.0 were found for pumpkin<sup>16</sup> and many common vegetables,<sup>17</sup> including root crops.<sup>71</sup> Lower ratios near 0.4 have been observed for grains.<sup>18,71,84</sup> From Table 2.4,  $C_r < C_v$  appears to apply to potassium, and thus the geometric mean of values determined for references 16-18, 71, and 84 was used to generate a value of  $B_r = 0.55$ . This estimate yields predicted  $C_r$  for potassium which agrees well with the observed range (Table 2.4).

One reference was found for rubidium  $B_v$ , but both default  $B_v$  and  $B_r$  values were derived by assuming systematic trends in  $B_v$  (Fig. 2.4) and  $(B_r/B_v)$  ratio (Fig. 2.6) for Group IA and IIA elements and comparing observed and predicted  $C_v$  and  $C_r$ . No references were found for francium  $B_v$ ,  $B_r$ ,  $C_v$ , or  $C_r$ ; and therefore, assumed systematic trends in  $B_v$  and  $(B_r/B_v)$  ratio were used exclusively for default estimates of the concentration factors. The  $B_v$  of 0.03 determined here for francium compares well with the value of 0.04 derived from Ng et al.<sup>15</sup> (assuming 25% dry matter).

Strontium is perhaps the best studied of all elements in the periodic table with respect to plant uptake. As for cesium, analysis of the references for  $B_v$  indicates that this parameter is lognormally distributed (Fig. 2.7). The range of reference mean values, 0.077 to 17, is larger than the range for cesium, but the number of references is also greater. The geometric mean of the reference means = 2.7, and it was rounded off to 2.5 for use in TERRA. Fifteen references applicable to  $B_r$  yielded a value of 0.25. Twenty-five references yielded estimates of  $(C_r/C_v)$ , which when multiplied by the default value of  $B_v$  also gave a  $B_r = 0.25$ .

A  $B_v = 0.01$  for beryllium was derived from reference 16. That reference also yielded a  $B_r = 0.0028$  for pumpkin, but examination of Figs. 2.4 and 2.6 suggest that a value of 0.0015 is more reasonable. Adoption of this value yields a predicted  $C_r$  value which is approximately an order of magnitude higher than reported values (Table 2.4). However, as noted by Shacklette et al.,<sup>53</sup> toxicity to plants is severe and measurable amounts are rarely observed in plants.

The  $B_v$  for magnesium (1.0) was determined from references 16 and 65. The geometric mean of values of  $(C_r/C_v)$  ratio for references 16, 18, and 71 was used to derive a  $B_r = 0.55$ . Predicted and observed  $C_v$  and  $C_r$  for magnesium agree well (Table 2.4).

Calcium  $B_v$  (3.5) was derived from references 16, 65, 71, and 72. Comparison of predicted and observed  $C_v$  values using this  $B_v$  value (Table 2.4) and comparison among other Group IIA elements for  $B_v$  in Fig. 2.4 support the reasonableness of this value. Calculated mean  $(C_r/C_v)$  ratios for calcium, strontium, barium, and radium, 0.081, 0.13, 0.18, and 0.095, respectively, suggested the adoption of a value of 0.1 for all Group IIA elements below magnesium. Thus,  $B_r = 0.35$  for calcium is used in TERRA. Comparison of predicted and observed  $C_r$  values using this  $B_r$  (Table 2.4) is good.

**Table 2.4. Comparison of observed and predicted concentrations of Group I A and II A elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Group IA					
Li	30	0.15 to 55	0.75	0.010 to 9.8	0.12
Na	6,300	700 to 20,000	470	15 to 3,500	350
K	14,000	1,000 to 77,000 <sup>e,f</sup>	14,000	7,800 to 28,000 <sup>e</sup>	7,500
Rb	100	18 to 400	15	1.0 to 50	7.0
Cs	5.0		0.40	$2.0 \times 10^{-3}$ to 0.35	0.15
Fr					
Group IIA					
Be	6.0	0.090	0.060	$1.0 \times 10^{-3}$	$9.0 \times 10^{-3}$
Mg	6,300	110 to 14,000 <sup>f,g</sup>	6,300	200 to 11,000 <sup>f,g</sup>	3,500
Ca	14,000	1,000 to 78,000 <sup>f</sup>	48,000	71 to 6,400 <sup>f,g</sup>	4,800
Sr	300	13 to 1,900	750	0.060 to 40	75
Ba	500	28 to 80	75	0.30 to 86	7.5
Ra	$8.0 \times 10^{-7}$	$2.6 \times 10^{-9}$	$1.2 \times 10^{-8}$	$1.1 \times 10^{-9}$	$1.2 \times 10^{-9}$

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 13.

<sup>f</sup>Reference 14.

<sup>g</sup>Reference 54.

The  $B_v$  for barium (0.15) was determined from references 16, 59, and 65. The default  $B_v$  value was calculated in a manner similar to that for calcium using Eq. (5). Observed and predicted  $C_v$  and  $C_r$  agree well (Table 2.4).

Because of its importance radiologically, the concentration factors for radium used in AIRDOS-EPA have been both highly scrutinized and criticized.<sup>95</sup> Reevaluations of the  $B_{iv1}$  and  $B_{iv2}$  values listed in Moore et al.<sup>1</sup> have been based on corrections of values reported in the literature<sup>12</sup> and subjective evaluation of the quality of the references.<sup>95</sup> Unfortunately, available references for calculation of soil-to-plant concentration factors for radium must all be judged subjectively (Table 2.5). However, separation of plants into the two categories in association with  $B_v$  and  $B_r$  eliminates inconsistencies in the  $B_{iv1}$  and  $B_{iv2}$  approach and suggests that only one available reference reports questionable results. The earliest reference found for radium soil-plant concentration factors, reported by Kirchmann and Boulenger in 1968,<sup>87</sup> has not been used in support of  $B_v$  and  $B_r$  here because their analytical technique is questionable<sup>95</sup> and yields extremely high values. Furthermore, the experimental technique for determination of radium used by Kirchmann and Boulenger has been questioned.<sup>95</sup> However, reference 87 does yield a ( $B_r/B_v$ ) ratio consistent with those for calcium, strontium, and barium. Insufficient criteria have been found for rejection of any of the remaining references.

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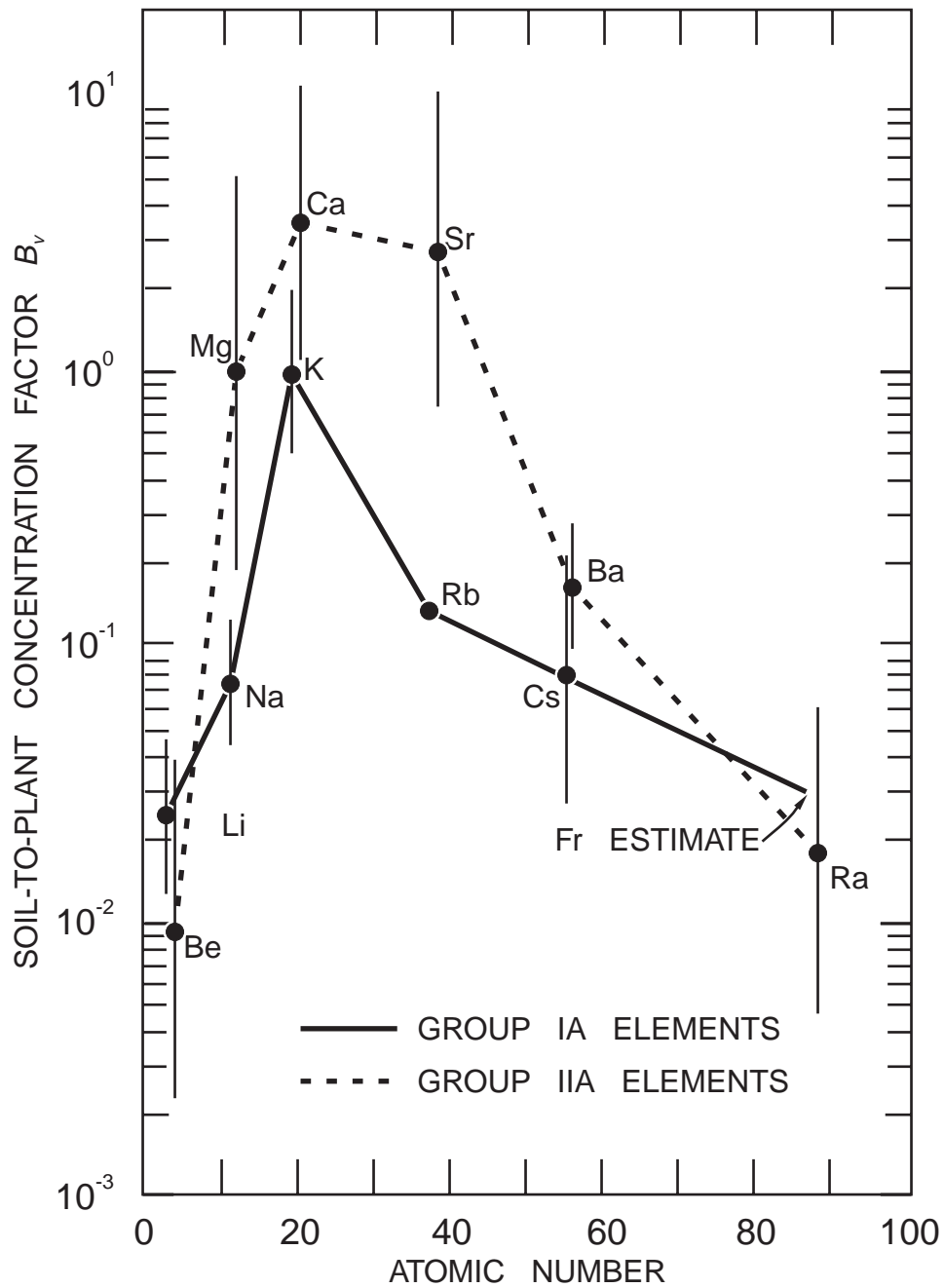


Figure 2.4. Assumed systematic trends in  $B_v$  for Group IA and IIA elements. Solid dots and error bars represent geometric means and standard deviations determined from available references.

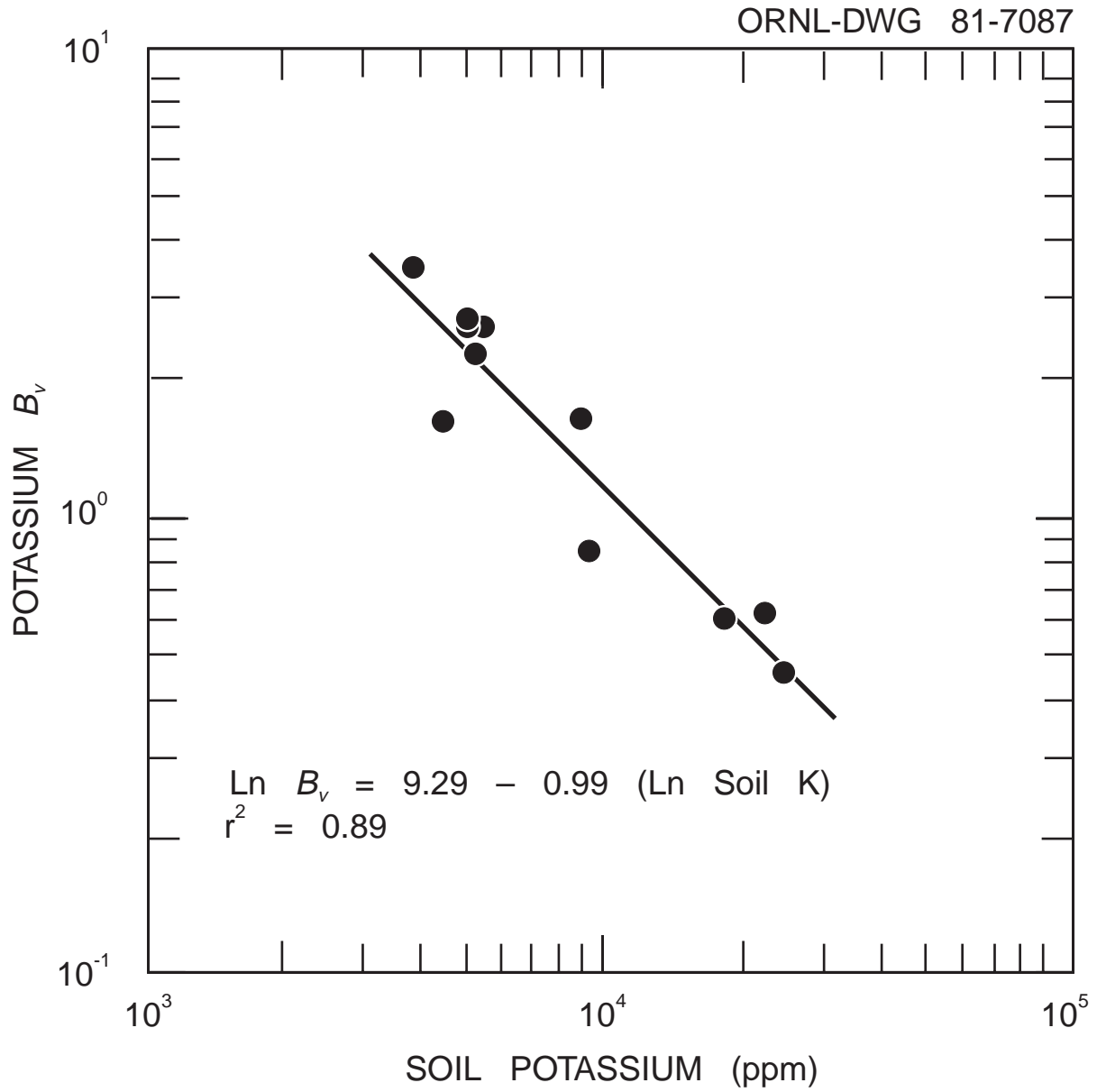


Figure 2.5. Correlation between soil potassium concentration and the soil-to-plant concentration factor,  $B_v$ , for potassium based on references 16 and 65.

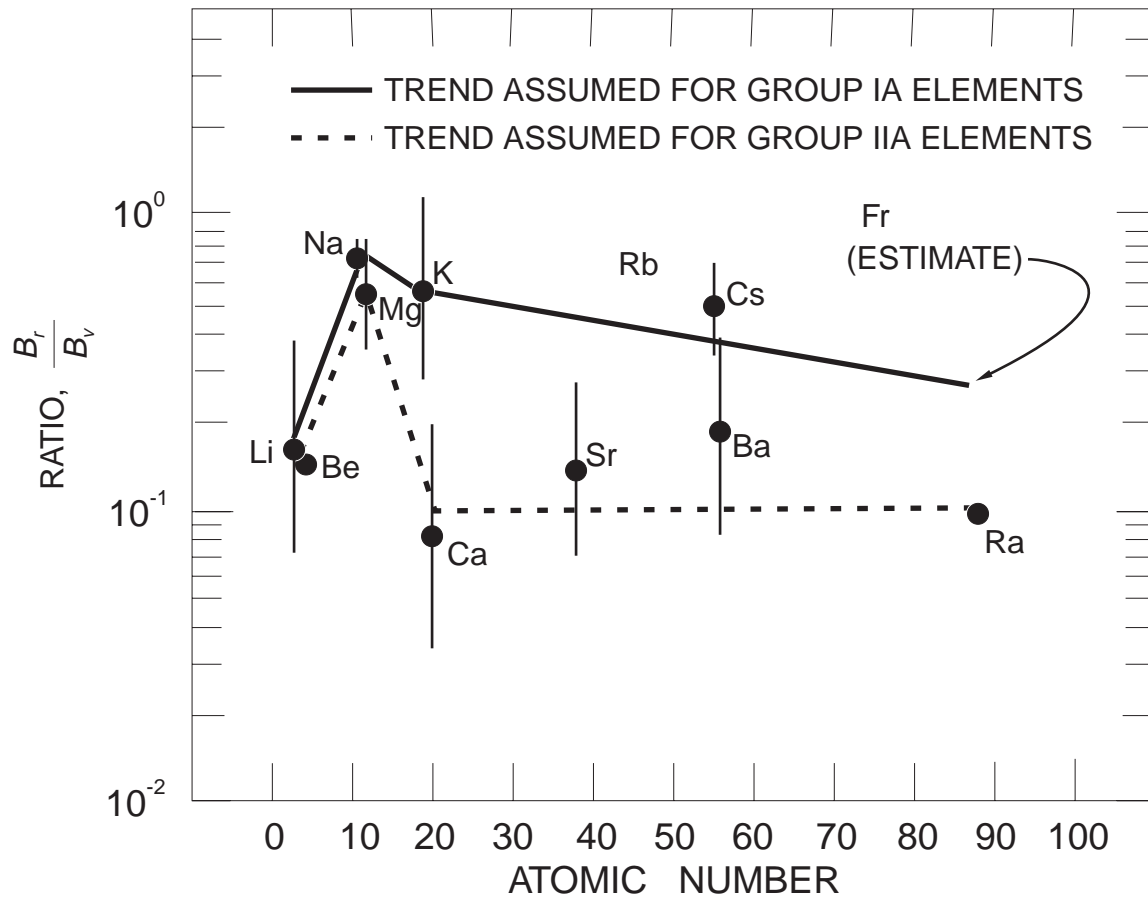


Figure 2.5. Assumed systematic trends in  $(B_r/B_y)$  ratio for Group IA and IIA elements. Solid dots and error bars represent geometric means and standard deviations determined from available references.

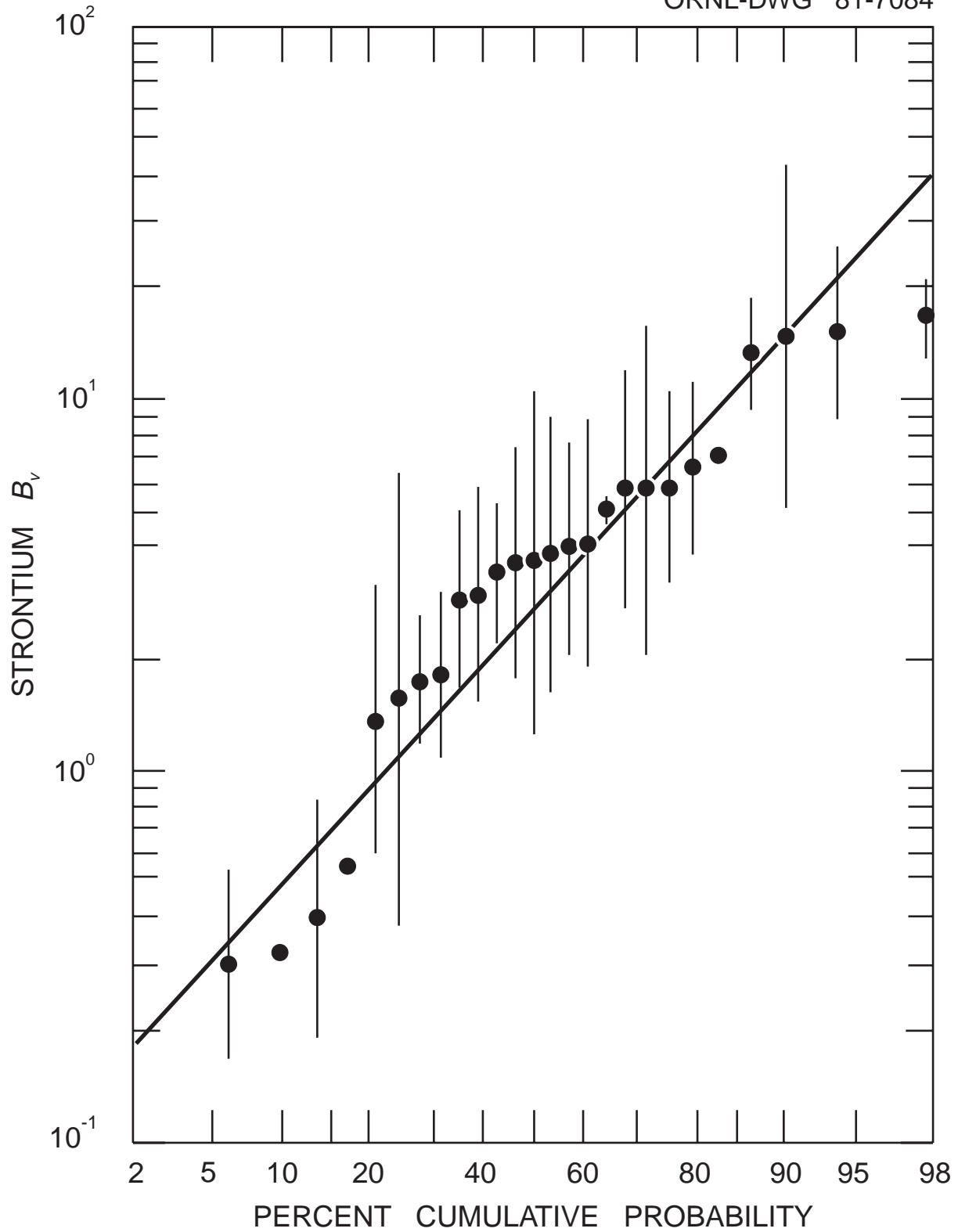


Figure 2.7. Lognormal probability plot of geometric means of  $B_v$  for strontium (calculated from references 11, 16, 17, 21, 31, 33, 59, 60, 62-70, 72, 74-76, 78, 81-83, 85, and 86), including one geometric standard deviation of the mean.



**Table 2.5. Literature values of  $B_v$ ,  $B_r$ , and the  $(C_r/C_v)$  ratio for radium<sup>a</sup>**

$B_v$	$B_r$	$(C_r/C_v)$	Reference	Comments
0.71	0.10	0.95	87	Ra-226 measurement technique questionable. Estimates of $B_v$ and $B_r$ not used in present analysis.
	$5.0 \times 10^{-4}$		90	Reported wet weight plant concentrations converted to dry weight using reference 13.
0.045	$3.2 \times 10^{-3}$		88	Values reported for "herbage and fruit" required assumptions as to exact makeup. Wet weight plant concentrations converted to dry weight using reference 14.
0.060		1.8	93	Vegetation sampled inappropriate to human pathways. Resuspension of soil onto plant surfaces suspected.
0.012			89	Pot geometry and soil bulk density assumed in order to estimate soil radium concentrations. Ash weight plant concentrations converted to dry weight using reference 13.
0.020			91	
$2.4 \times 10^{-3}$	$8.2 \times 10^{-4}$		92	"Salad" was assumed to be lettuce. Ash weight plant concentrations converted to dry weight using reference 14.

<sup>a</sup>Geometric means of all values reported.

In a review of Ra-226 transport by McDowell-Boyer, Watson, and Travis,<sup>96</sup> a value of 0.09 was recommended for a radium forage and hay concentration factor. The authors recommended a value of 0.02 for vegetables, fruit, and grain. The dry weight equivalent of this value would be a factor of 4 to 10 higher, depending on the assumed water content of vegetables, fruit, and grains. The value for  $B_v$  derived from five references listed in Table 2.5 is 0.017, which is roughly a factor of 5 lower than the value recommended in reference 96. This value has been rounded off to 0.015. The  $B_r$  value derived from three references listed in Table 2.5 is 0.0011, which is much lower than the value recommended in reference 96. The  $(B_r/B_v)$  ratio obtained from reference 87 and similar ratios found for calcium, strontium, and barium suggest that a  $B_r = 0.0015$  is reasonable. These default  $B_v$  and  $B_r$  values appear to be acceptable based on systematic trends (Figs. 2.4 and 2.6) for Group IIA elements and comparison of observed and predicted  $C_v$  and  $C_r$  values (Table 2.4).

Much work has been done on the effect of available soil calcium on the uptake of strontium by plants,<sup>18,21,33,71,78,79,81,82</sup> and this subject has been thoroughly reviewed by Francis;<sup>233</sup> in general, plant uptake of strontium is inversely proportional to the amount of exchangeable calcium in the soil. The same effect of soil calcium on plant uptake of radium has also been suggested.<sup>88</sup> Therefore, it is likely that plant uptake of all Group IIA elements will be negatively affected by increasing soil calcium. The exact relationships between calcium and other IIA elements will be affected by plant type, plant part, and soil characteristics; therefore, in the TERRA computer code, soil calcium influence on  $B_v$  and  $B_r$  for Group IIA elements is not considered. However, a user of the code may wish to select higher  $B_v$  and  $B_r$  values than the defaults (Figs. 2.1 and 2.2) for Group IIA elements for pasture pathways and lower values for food crop pathways, assuming that in the latter case soils are more intensively prepared and amended (including liming).

### 2.1.3 Group IIIA, IVA, and VA elements

Groups IIIA, IVA, and VA contain elements which are essential plant nutrients, elements for which some isotopes are important radiologically, and elements for which experimental evidence for  $B_v$  and  $B_r$  is scanty. By far, the best documented element of these groups for  $B_v$  and  $B_r$  is lead,<sup>16,20,27,91,99-105</sup> followed by arsenic,<sup>16,19,98</sup> boron,<sup>16,17,65,76</sup> aluminum,<sup>16,17,19,65</sup> phosphorus,<sup>16,17,97</sup> indium,<sup>65</sup> tin,<sup>65</sup> and antimony.<sup>65</sup> No references were readily obtainable for nitrogen, silicon, gallium, germanium, thallium, and bismuth. Corollary information was used to estimate transfer parameters for these elements.

The  $B_v$  value of 4.0 adopted for boron is based on the relationship between soil boron concentration and boron  $B_v$  determined from references 16, 65, and 76 (Fig. 2.8), and an assumed average soil boron concentration of 10 ppm (Table 2.6).<sup>52</sup> The ( $B_r/B_v$ ) ratio as determined from references 16 and 17 is approximately 0.5, and a  $B_r$  value of 2.0 was adopted. Comparison of observed and predicted boron food concentrations (Table 2.6) indicates that the default  $B_v$  and  $B_r$  values are reasonable.

The  $B_r$  estimate of 0.004 for aluminum is based on references 16 and 65. The ( $B_r/B_v$ ) ratio of 0.167 determined from reference 17 was used to generate a default value for  $B_r$  of  $6.5 \times 10^{-4}$ . This value is a factor of 2.5 greater than the single value of  $2.6 \times 10^{-4}$  found by Baes and Katz,<sup>16</sup> but comparison of observed and predicted aluminum concentrations in produce (Table 2.6) indicates the default  $B_v$  and  $B_r$  estimates give reasonable predictions which are near the low end of reported ranges.

The  $B_v$  for indium was taken from a single value determined from reference 65. Because the default  $B_v$  estimate for indium equals the default  $B_v$  estimate for aluminum, a gallium  $B_v$  of 0.004 was also assumed for this Period IV element. Since no data were available for thallium  $B_v$ , its value was set equal to that for aluminum, gallium, and indium. A ( $B_r/B_v$ ) ratio of 0.1 was assumed for gallium, indium, and thallium, yielding a  $B_r$  of  $4.0 \times 10^{-4}$  for these elements. Unfortunately, elemental concentrations of gallium, indium, and thallium in soils and a variety of produce are not well-documented. However, the values assumed here are consistent with the fragmentary information of observed plant concentrations of these elements.

Of the Group IVA elements, lead is the best documented with respect to  $B_v$  and  $B_r$ . The default  $B_v$  value of 0.045 is the geometric mean of values determined for nine references. A ( $B_r/B_v$ ) ratio of 0.2 based on references 16, 20, 27, 99 and 102 yields a  $B_r$  estimate of 0.009. Table 2.6 shows that these  $B_v$  and  $B_r$  default values yield appropriate estimates of lead concentrations in produce.

No references for the direct measurement of  $B_v$  or  $B_r$  for silicon were found. Ng et al.<sup>15</sup> provide data from which a dry weight transfer factor of  $6.1 \times 10^{-4}$  can be derived. Menzel,<sup>106</sup> however, reported that the transfer coefficient for soluble forms of silicon ranged between 0.1 and 1.0. Using the 330,000 ppm (33%) value for silicon in soil reported by Vinogradov<sup>52</sup> and the  $C_v$  range reported by Shacklette et al.,<sup>53</sup> the Ng et al. value is approximately an order of magnitude too low and the range reported by Menzel is too high. Therefore, for a  $B_v$  estimate, the  $C_v$  value reported for grasses of 110,000 ppm silicon (plant concentrations for other produce or vegetables were reported in wet or ash weight) was combined with the reported average soil concentration according to Eq. (3) to give a  $B_v = 0.35$  for silicon. The ( $B_r/B_v$ ) ratio for silicon was assumed to be the same as for lead, generating a  $B_r$  estimate of 0.07.

Reference 15 yields a dry weight transfer factor of 0.4 for germanium. This value appears to be slightly low when predicted and measured  $C_v$  values are compared (Table 2.6). However, in the absence of experimental evidence and because the value agrees well with the default  $B_v$  estimate for silicon, it is used for germanium  $B_v$  also. The ( $B_r/B_v$ ) ratio is also assumed to be 0.2 as for lead and silicon, yielding a  $B_r$  estimate of 0.08.

The  $B_v$  for tin of 0.03 is based on reference 65, and the  $B_r$  value of 0.006 is based on an assumed ( $B_r/B_v$ ) ratio of 0.2. Comparison of observed and predicted  $C_v$  and  $C_r$  values in Table 2.6 indicates that the default  $B_v$  and  $B_r$  values are reasonable.

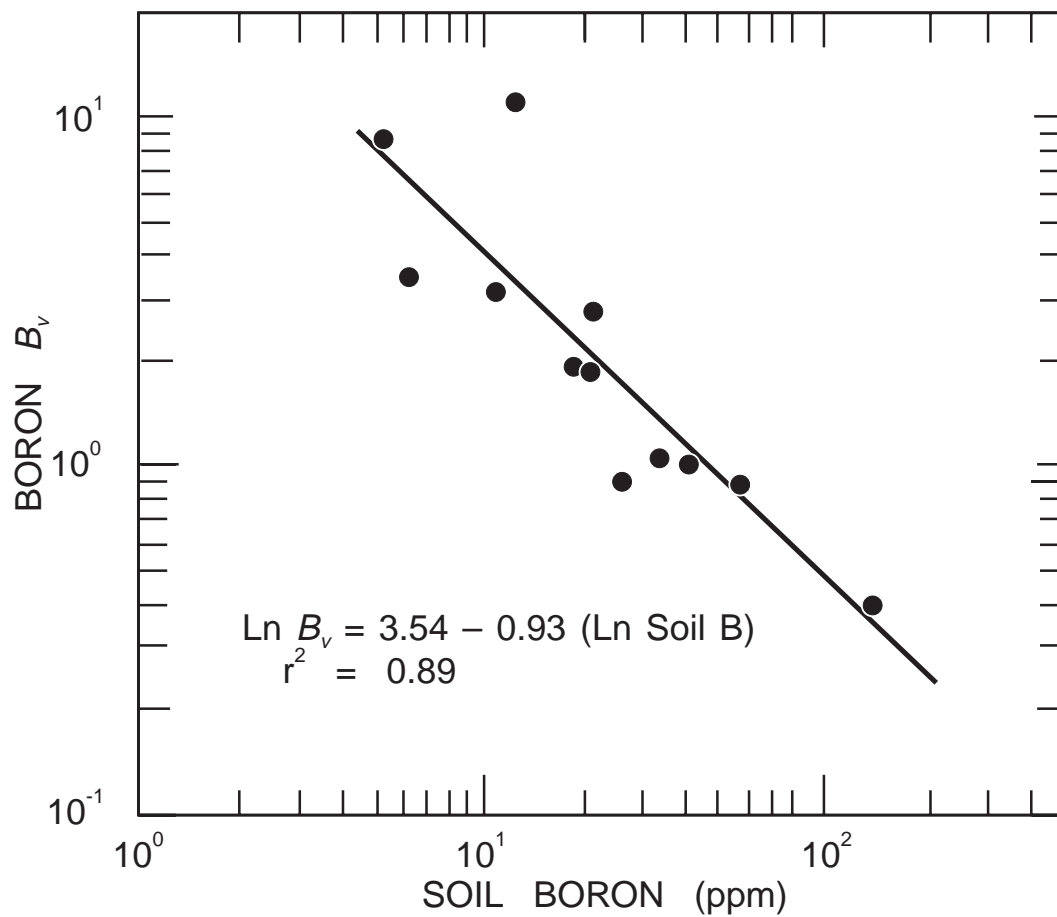


Figure 2.8. Correlation between soil boron concentration and the soil-to-plant concentration factor,  $B_v$ , for boron based on references 16, 65, and 76.

**Table 2.6. Comparison of observed and predicted concentrations of Group III A, IV A, and V A elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Group III A					
B	10	4.0 to 2,100	40	66 to 520	20
Al	71,000	900	280	11 to 86	46
Ga	30	0.13	0.12		0.012
In					
Tl		0.26 to 0.90			
Group IV A					
Si	330,000	24,000 to 110,000	120,000		23,000
Ge	1.0	0.64 to 13	0.40		0.080
Sn	10	0.13	0.30	0.10 to 1.8	0.060
Pb	10	0.13 to 9.0	0.45	0.015 to 1.0	0.090
Group V A					
N	1,000	16,000 to 43,000 <sup>e</sup>	30,000	4,500 to 29,000 <sup>e,f</sup>	30,000
P	800	600 to 9,800 <sup>e</sup>	2,800	630 to 52,000 <sup>f</sup>	2,800
As	5.0	<0.05 to 0.25	0.20	<0.05 to 3.9	0.030
Sb	0.10	<0.056 <sup>g</sup>	0.020	$1.3 \times 10^{-4}$ to 0.039 <sup>g</sup>	$3.0 \times 10^{-3}$
Bi	1.0	0.15	0.035	0.068	$5.0 \times 10^{-3}$

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 14.

<sup>f</sup>Reference 13.

<sup>g</sup>Reference 54.

No references for experimental determination of  $B_v$  for the essential plant nutrient nitrogen were readily available. The review reference 15 yields a default value of 30, which gives a predicted  $C_v$  in the midrange of reported values (Table 2.6). Thus, this value was adopted for use in TERRA. Comparison of observed  $C_v$  and  $C_r$  ranges indicates that nitrogen uptake in vegetative and reproductive plant parts is approximately the same. In the absence of evidence to the contrary,  $B_v = B_r$  was assumed.

The  $B_v$  for phosphorus is based on the relationship between soil phosphorus concentration and  $B_v$  found from data in reference 16 (Fig. 2.9), assuming an average soil concentration of phosphorus of 800 ppm.<sup>52</sup> Three references yield estimates of ( $B_r/B_v$ ) ratio. Two references (16 and 97) yield estimates greater than 1.0. Reference 17 yields a value of 0.78, but one standard deviation of the mean includes 1.0. Thus as for nitrogen,  $B_v = B_r$  was adopted. Comparison of observed and predicted  $C_v$  and  $C_r$  indicates that default values of  $B_v$  and  $B_r$  for phosphorus are reasonable.

The  $B_v$  for arsenic of 0.04 was determined from references 16 and 98. References 16 and 19 both indicate that, unlike the lighter members of Group VA elements, the accumulation of arsenic in nonvegetative plant parts is less than for vegetative parts. A ( $B_r/B_v$ ) ratio for arsenic of 0.15 was used to calculate a default  $B_r = 0.006$ . Comparison of observed and predicted  $C_v$  and  $C_r$  values (Table 2.6) shows that the default  $B_v$  predicts  $C_v$  values near the high end of the observed range and the  $B_r$  predicts  $C_r$  values near the low end of the observed range.

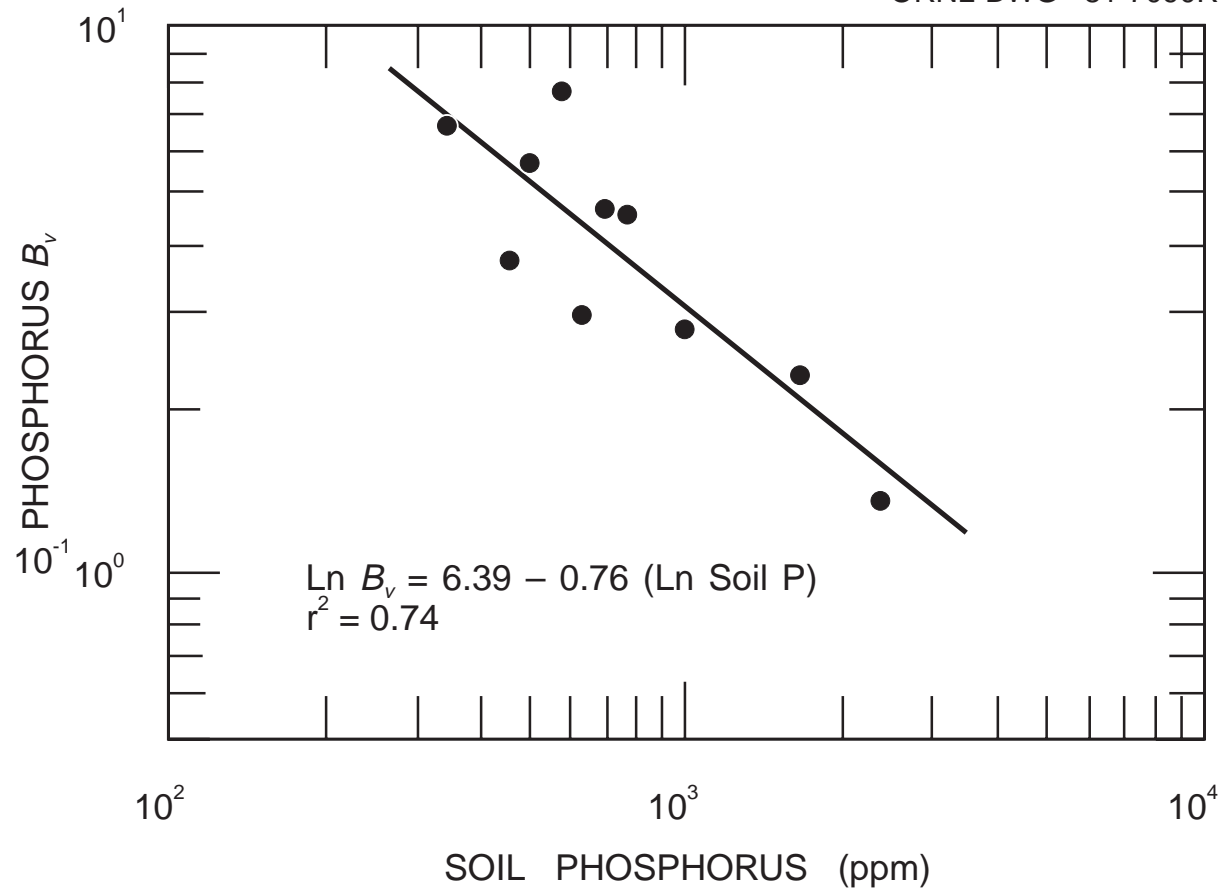


Figure 2.9. Correlation between soil phosphorus concentration and the soil-to-plant concentration factor,  $B_v$ , for phosphorus based on reference 16.

The  $B_v$  for antimony was taken from reference 65. The  $(B_r/B_v)$  ratio for arsenic was also used for antimony. Comparisons of observed and predicted  $C_v$  and  $C_r$  for arsenic (Table 2.6) are reasonably good.

The  $B_v$  for bismuth was determined from the  $B_v$  estimates for lead and polonium (discussed in Sec. 2.1.4). The  $B_r$  estimate was generated from the default  $B_v$  of 0.035 and the  $(B_r/B_v)$  ratio used for arsenic and antimony. Comparison of observed and predicted  $C_v$  and  $C_r$ , although not definitive, are relatively good (Table 2.6).

### 2.1.4 Group VIA and VIIA elements

The Group VIA and VIIA elements include the relatively mobile anions and the radiologically important elements polonium and iodine. Of these elements the best documented are iodine,<sup>25,59,65,107,234,235</sup> selenium,<sup>19,65,76</sup> and polonium.<sup>28,91</sup> Single references were available for fluorine,<sup>108</sup> chlorine,<sup>65</sup> and bromine,<sup>65</sup> and no references were readily available for sulfur, tellurium, and astatine.

No references on direct determination of soil-to-plant transfer coefficients for sulfur were readily available. However, assuming an average sulfur concentration of 1400 ppm in vegetative portions of plants<sup>14</sup> and 850 ppm in soil,<sup>52</sup> a  $B_v$  of 1.5 results. Comparison of observed  $C_v$  and  $C_r$  for sulfur indicate that  $B_v = B_r$  for this element (Table 2.7).

The default  $B_v$  value for selenium of 0.025 was determined via several approaches. The value obtained from references 65 and 76 (0.032) was compared with values given by Ng et al.<sup>15</sup> and Menzel.<sup>106</sup> The latter two estimates were several orders of magnitude higher than the value obtained from references 65 and 76. Although  $B_v$  for plant-fly ash relationships<sup>19,65,76</sup> is comparable to  $B_v$  estimates given by Ng et al.<sup>15</sup> and Menzel,<sup>106</sup> their estimates, when combined with an average selenium soil concentration of 1 ppm, tend to over-predict observed  $C_v$  values (Table 2.7). Therefore, as a model for selenium the As/P and Br/Cl  $B_v$  ratios were used as analogs for the Se/S  $B_v$  ratio. If such ratios are assumed to change systematically, then the Se/S ratio may be assumed to be 0.016. This value, multiplied by the  $B_v$  for sulfur, yields a default selenium  $B_v$  estimate of 0.025. Comparison of observed and predicted selenium  $C_v$  using this default value (Table 2.7) suggests that the default value is reasonable. Although the  $(B_r/B_v)$  ratio for selenium taken from reference 19 is less than 1.0, comparison of observed  $C_v$  and  $C_r$  ranges suggest that  $B_v = B_r$  for selenium also.

The  $B_v$  for polonium based on references 28 and 91 is  $2.5 \times 10^{-3}$ . The  $(B_r/B_v)$  ratio taken from reference 28 is 0.15. This ratio generates a default  $B_r$  value of  $4.0 \times 10^{-4}$ . Unfortunately, no references for comparison of observed  $C_v$  and  $C_r$  were immediately available for comparison with predicted values.

No references were found for tellurium. The default  $B_v$  values determined for selenium and polonium suggest that a reasonable assumption for tellurium  $B_v$  is also a value of 0.025. Correspondingly, the  $(B_r/B_v)$  ratio of 0.15 for polonium was used to predict a  $B_r$  for tellurium of 0.004. As for polonium, no observed  $C_v$  and  $C_r$  values were available. Furthermore, no average tellurium soil concentrations were available either.

The  $B_v$  for fluorine is based on reference 108. The value of 0.06 generates a predicted  $C_v$  value which falls within the range of observed values (Table 2.7). Comparison of observed  $C_v$  and  $C_r$  ranges suggest a discrimination factor of approximately an order of magnitude. Thus, a  $(B_r/B_v)$  ratio of 0.1 was assumed and  $B_r = 0.006$ .

The  $B_v$  and  $B_r$  for chlorine were determined through comparison of observed  $C_v$  and  $C_r$  and average  $C_s$  for chlorine (Table 2.7). Both the resulting  $B_v$  and  $B_r = 70$ , the highest concentration factors for any element reviewed here. Reference 65 yielded a  $B_v$  of 2.1 and a value of 20 was obtained from reference 15, but the  $C_v$  predicted with these factors are well below the reported range. Thus the more indirect method was deemed more appropriate for chlorine.

**Table 2.7. Comparison of observed and predicted concentrations of Group VI A  
VII A elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Group VI A					
S	850	100 to 17,000 <sup>e</sup>	1,300	200 to 450 <sup>e</sup>	1,300
Se	1.0 <sup>f</sup>	<0.01 to 0.35	0.025	<0.01 to 0.50	0.025
Te					
Po	$1.0 \times 10^{-11}$		$2.5 \times 10^{-14}$		$4.0 \times 10^{-15}$
Group VII A					
F	200	1.3 to 28	12	0.020 to 8.4	1.2
Cl	100	2,000 to 23,000	7,000	300 to 8,500	7,000
Br	5.0	0.31 to 4.9	7.5	0.20 to 260	7.5
I	5.0	4.3 to 10	0.75	2.8 to 10	0.25
At					

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 14.

<sup>f</sup>Based on values given in references 65 and 76.

The  $B_v$  for bromine is based on reference 65. Although the corresponding predicted  $C_v$  is slightly high with respect to the observed  $C_v$  range, comparison of observed  $C_v$  and  $C_r$  ranges suggest that the reported  $C_v$  range may be low (the upper end of the  $C_r$  range is higher than that for the  $C_v$  range and a discrimination factor of greater than 1.0 for  $C_r$  appears unlikely). In lieu of contrary information, a ( $B_r / B_v$ ) ratio of 1.0 was assumed for bromine, and thus  $B_v = B_r$  was assumed.

The  $B_v$  for iodine (0.15) is the geometric mean of values determined for references 25, 59, 65, 107, 234, and 235. References 59 and 107 indicate that  $B_v$  for iodine ranges between 1.0 to 2.0. However, references 65, 234, and 235 indicate a much lower  $B_v$  for iodine (0.04 to 0.10). Menzel<sup>106</sup> reports that the concentration factor for bromine is greater than that for iodine, and examination of Table 2.7 shows that the adopted  $B_v$  for iodine does not predict a  $C_v$  value greater than observed. Thus, the default value adopted in the TERRA code seems reasonable.

The  $B_v$  value of 0.050, adopted as a default in TERRA, is based on a compromise between the value of 0.02 derived from reference 234 and the product of the  $B_r/B_v$  ratio (0.5) derived from references 25 and 234 and the default  $B_v$  of 0.15. Examination of Table 2.7 shows that the default  $B_r$  value does not over-predict observed  $C_r$  values reported in the literature.

No references were found for astatine. A value of 1.0 for  $B_v$  is derived from Ng et al.,<sup>15</sup> and this value is adopted as a default value for TERRA. Using polonium as an analog, the assumed ( $B_r/B_v$ ) ratio is 0.15, producing a  $B_r = 0.15$ .

### 2.1.5 Group IIIB and the rare earth elements

The Group IIIB and the rare earth or lanthanide series elements are generally not important for plant nutrition, nor do they accumulate to any large extent in plants. Radiologically, isotopes of cerium are important. In our analysis, we found yttrium<sup>16,22,59,60,67</sup> and cerium<sup>22,59,60,65</sup> to be the best documented of these elements, followed by scandium,<sup>65</sup> lanthanum,<sup>65</sup> promethium,<sup>22,59</sup> samarium,<sup>65</sup> and ytterbium.<sup>65</sup> No references were obtained for praseodymium, neodymium, europium, gadolinium, terbium, dysprosium, holmium, erbium, and thulium. However, because of the similarity of chemical behavior of all the lanthanides,<sup>110,111</sup> soil-to-plant concentration factors for these undocumented elements are based on our analysis of cerium. The  $B_v$  for yttrium of 0.015 was derived from references 16, 22, 59, 60, and 67. A  $(C_r/C_v)$  ratio of 0.29 was determined from references 16, 22, and 60 and compared with a  $(B_r/B_v)$  ratio of 0.46 which was based on a  $B_r$  derived from these same references. A  $(B_r/B_v)$  ratio midway between these two estimates (0.36) was used to derive a default  $B_r = 0.006$ . Comparison of observed and predicted  $C_v$  and  $C_r$  for yttrium (Table 2.8) indicate that the default  $B_v$  and  $B_r$  values are perhaps slightly low, but not unreasonable.

The  $B_v$  for scandium of 0.006 is based on the observation by Baes and Mesmer<sup>110</sup> that the chemistry of scandium is between that for aluminum (Sect. 2.1.3) and that for yttrium, but surprisingly more like that for aluminum. A value of 0.0078 was taken from reference 65, and data from Ng et al.<sup>15</sup> yields a value of 0.0043. The mean of these two values corresponds well with the value of 0.006 determined through systematic interpretation of Baes and Mesmer's observation (Fig. 2.10). The  $(B_r/B_v)$  ratio was determined in a similar manner to  $B_v$  assuming a systematic variation in this parameter. The ratio value of 0.2 was used to calculate a default  $B_r = 0.001$ . Comparison of observed and predicted scandium food concentrations (Table 2.8) are difficult because of the uncertainty in the observed range values. However, if the observed  $C_r$  range reported is reasonable, then both predicted  $C_r$  and  $C_v$  values are not unreasonable.

The  $B_v$  for cerium of 0.01 was derived from references 22, 59, 60, and 65. Because of the similarity in the lanthanide elements, the  $B_v$  values from references 22, 59, and 65 for other members of the series were pooled with and without those for cerium to estimate  $B_v$  for all of the lanthanides. Both sets of pooled references yielded a  $B_v = 0.01$ . Thus, this value was adopted for elements 57 through 71. Pooling of references for  $(B_r/B_v)$  ratio<sup>22,60</sup> yielded a value of 0.4. This value was also used for elements 57 through 71.

Comparisons of observed and predicted lanthanide concentrations in produce and plants is difficult because of the paucity of good experimental information. However, examination of Table 2.8 shows that for elements in which comparisons can be made, our soil-to-plant transfer coefficients tend to slightly underpredict reported food concentrations. Although some underpredictions are by more than an order of magnitude, the uncertainty involved in a typical soil concentration or the applicability of a few measurements to the true range of food concentrations does not warrant revision of the estimates.



**Table 2.8. Comparison of observed and predicted concentrations of Group IIIB and the rare earth elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Sc	7.0	$1.0 \times 10^{-4e}$	0.042	$5.0 \times 10^{-5}$ to $0.10^{b,e}$	$7.0 \times 10^{-3}$
Y	50	2.7 to 9.1	0.75	0.40 to 4.5	0.30
La	40	<0.074	0.40	0.052 to $0.31^e$	0.16
Ce	50	0.084	0.50	$0.033$ to $0.10^{b,e}$	0.20
Pr	4.5		0.045		0.18
Nd	18		0.18	0.080	0.072
Pm				0.080	
Sm	4.9		0.049	0.080	0.020
Eu	0.39	$<5.3 \times 10^{-3e}$	$3.9 \times 10^{-3}$	0.080	$1.6 \times 10^{-3}$
Gd	5.5		0.055	0.080	0.022
Tb	0.85		$8.5 \times 10^{-3}$	0.080	$3.4 \times 10^{-3}$
Dy	6.0		0.060	0.080	0.024
Ho	0.95		$9.5 \times 10^{-3}$	0.080	$3.8 \times 10^{-3}$
Er	4.5		0.045	0.080	0.018
Tm	0.45		$4.5 \times 10^{-3}$	0.080	$1.8 \times 10^{-3}$
Yb	4.6	0.53 to 3.2	0.046	0.080 to 13	0.018
Lu	1.2		0.012	0.080	$4.8 \times 10^{-3}$

<sup>a</sup>Sc-Ce from reference 52; Pr-Lu estimated from ranges reported by Gibson et al.<sup>111</sup>

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 54.

### 2.1.6 Period IV transition elements

Elements of atomic number 22 through 30 (titanium through zinc) are perhaps the best documented for plant uptake from soil. Several of these elements, including manganese, iron, and zinc are generally accepted as essential plant micronutrients.<sup>53</sup> Others, including chromium and cobalt, are recognized as essential for animal nutrition and are suspected as plant nutrients, although their essentiality has not been established. Stable isotopes of these elements have been extensively studied because most are toxic to plants and animals at sufficient concentrations, although radiologically they are relatively unimportant. As the following discussion will show, the concept of a single equilibrium concentration factor for many of these elements can be questioned. For those elements which are essential to plant nutrition, and thus are likely to be regulated by the plant, correlations between soil concentrations and  $B_v$  have been established in a manner similar to those for potassium, phosphorus, and nitrogen.

Available references for  $B_v$ ,  $B_r$ , and  $(B_r/B_v)$  ratio numbered 16 for zinc;<sup>16,17,19,20,35,37,65,67,97,104,114-119</sup> nine for manganese;<sup>16,17,19,36,37,65,104,112,113</sup> eight for copper;<sup>16,17,19,20,65,104,114,115</sup> five for nickel,<sup>16,20,102,104,114</sup> iron,<sup>16,17,19,65,104</sup> and cobalt;<sup>16,17,19,65,104</sup> four for chromium;<sup>16,19,65,102</sup> three for titanium;<sup>16,19,65</sup> and two for vanadium.<sup>16,65</sup> Correlations between soil concentrations and  $B_v$  were found for all but vanadium, titanium, and nickel. These correlations were often used in lieu of the geometric means approach to define default  $B_v$  values.

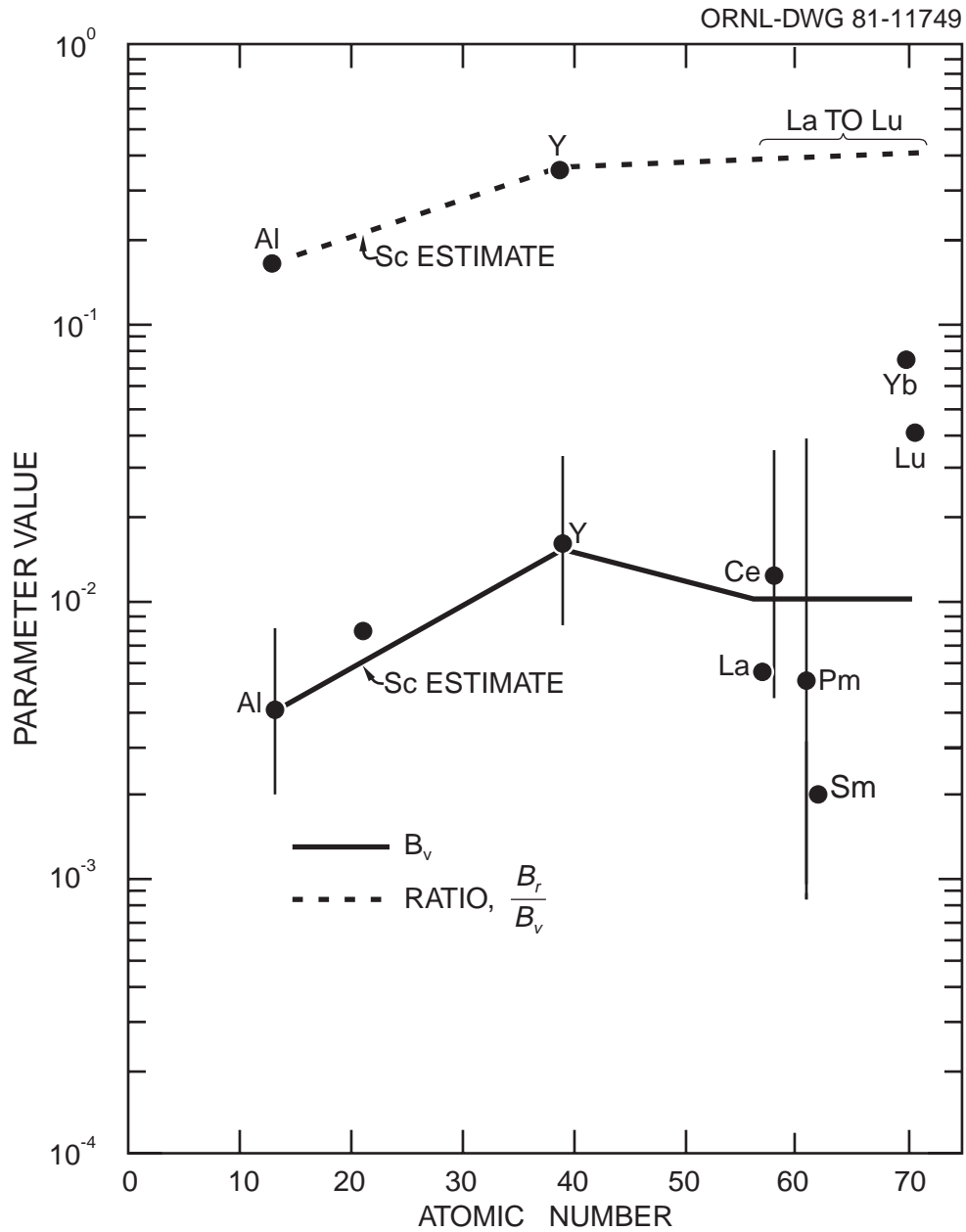


Figure 2.10. Assumed systematic trends in  $B_v$  and  $(B_r/B_v)$  ratio for aluminum, scandium, and yttrium. Solid dots and error bars represent geometric means and standard deviations of the mean determined from available references.

As before, predicted plant concentrations were compared with observed values in order to assure reasonable  $B_v$  and  $B_r$  estimates. These approaches were used in lieu of elemental systematics because subsequent analyses (see Sec. 2.1.7 and 2.1.8) depended heavily on the values obtained for these Period IV elements.

The  $B_v$  for titanium of 0.0055 is the geometric mean derived from references 16 and 65. The  $B_r$  value was generated from a  $(B_r/B_v)$  ratio derived from reference 19. Both soil-to-plant concentration factors predict plant concentrations from typical soil titanium concentrations which agree well with observed plant concentrations (Table 2.9).

The  $B_v$  for vanadium was also derived from references 16 and 65, and it is numerically equal to the  $B_v$  for titanium. No information was available on the  $(B_r/B_v)$  ratio for vanadium, and therefore, it was assumed equal to that for titanium, yielding a  $B_r = 0.003$ . Comparison of observed and predicted  $C_v$  and  $C_r$  for vanadium (Table 2.9) is also good.

References 16 and 65 yield a  $B_v$  by the geometric means method of 0.03 for chromium. However, a correlation between soil chromium concentration and chromium  $B_v$  was observed from the data in these two references (Fig. 2.11). Although this correlation is weak, the  $B_v$  determined by geometric means predicts  $C_v$  for chromium greater than the observed range. Therefore, the relationship in Fig. 2.11 was used to predict a chromium  $B_v$  of 0.0075 at a soil chromium concentration of 200 ppm.<sup>52</sup> This value of  $B_v$  does predict a reasonable  $C_v$ , (Table 2.9).

A  $(B_r/B_v)$  ratio of 0.6 for chromium was determined from references 16, 19, and 102. This value generates a  $B_r = 0.0045$ , which predicts a  $C_r$  within the reported range of observed  $C_r$  values (Table 2.9).

The  $B_v$  for manganese generated by the geometric means method is 0.41. However, from data in references 16, 36, 37, 104, 112, and 113 a strong correlation between  $B_v$  and soil manganese concentration was observed (Fig. 2.12). At a typical soil manganese concentration of 850 ppm,<sup>52</sup> the corresponding  $B_v = 0.25$ . This latter value was adopted for TERRA. Although this latter  $B_v$  value for manganese overpredicts  $C_v$  with respect to the reported observed range, the former value overpredicts  $C_v$  by an even larger factor.

The  $(B_r/B_v)$  ratio for manganese of 0.2 was determined from references 16, 17, and 19. This ratio generates a  $B_r = 0.05$ . Comparison of observed and predicted  $C_r$  using this  $B_r$  value (Table 2.9) indicates that the default  $B_r$  is reasonable.

Iron is an essential plant nutrient, and therefore, root uptake is probably regulated by the plant. It is not surprising that the relationship between soil iron concentration and  $B_v$  shown in Fig. 2.13 was found. At a typical soil iron concentration of 3.8%,<sup>52</sup> the corresponding  $B_v = 0.004$ . The  $(B_r/B_v)$  ratio based on references 16, 17, and 19 = 0.25, yielding a  $B_r$  of 0.001. Comparison of observed and predicted  $C_v$  and  $C_r$  (Table 2.9) for iron indicates the reasonableness of the default  $B_v$ , and  $B_r$ .

The  $B_v$  for cobalt of 0.02 is based on the weak correlation between soil cobalt concentration and  $B_v$  (Fig. 2.14) and a typical soil cobalt concentration of 8 ppm.<sup>52</sup> A  $(B_r/B_v)$  ratio of 0.35 was derived from references 16, 17, and 19. This ratio generates a  $B_r = 0.007$ . Predicted  $C_v$  and  $C_r$  using these default concentration factors for cobalt agree well with observed  $C_v$  and  $C_r$  ranges (Table 2.9).

The  $B_v$  for nickel is based on references 16 and 104. Unlike chromium, manganese, iron, and cobalt, no clear relationship between soil nickel concentration and  $B_v$  was indicated from the available data. Also, unlike the other Period IV transition elements no discrimination factor between vegetative and nonvegetative plant parts was found. In fact, the geometric mean of references 16, 20, 102, and 114 for  $(B_r/B_v)$  ratio was 1.2. Therefore, a  $(B_r/B_v)$  ratio of 1.0 was assumed and  $B_v = B_r$  for nickel. Examination of Table 2.9 indicates that the observed  $C_r$  range includes the  $C_v$  range, supporting this assumption. Predicted  $C_v$  and  $C_r$  values agree well with reported observed ranges.

The  $B_v$  for copper is based on the strong correlation between soil copper concentration and  $B_v$  shown in Fig. 2.15 and an average soil copper concentration of 20 ppm.<sup>52</sup> The  $(B_r/B_v)$  ratio, as

**Table 2.9. Comparison of observed and predicted concentrations of Group IV transition elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Ti	4,600	1.6 to 160	25	0.087 to 80	14
V	100	<0.091 to 21	0.55	$4.60 \times 10^{-4}$ to 47	0.30
Cr	200	0.18 to 2.9	1.5	0.030 to 8.0	0.90
Mn	850	1.9 to 16	210	8.0 to 80	43
Fe	38,000	6.5 to 410 <sup>e</sup>	150	10 to 160 <sup>e</sup>	38
Co	8.0	0.010 to 0.54	0.16	$6.0 \times 10^{-3}$ to 0.36	0.056
Ni	40	0.23 to 5.2 <sup>b,f</sup>	2.4	0.028 to 10	2.4
Cu	20	1.7 to 11	8.0	0.80 to 27	5.0
Zn	50	2.5 to 630	75	0.50 to 110	45

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 14.

<sup>f</sup>Reference 54.

determined from references 16, 17, 19, 20, and 114, equals 0.63. This ratio yields a  $B_r = 0.25$ . Both soil-to-plant concentration factors yield reasonable predicted plant copper concentrations (Table 2.9).

The  $B_v$  for zinc was determined from the strong correlation between soil zinc concentration and  $B_v$  determined from references 16, 35, 37, 67, 97, 104, 114, 115, 117, and 119 (Fig. 2.16) and an average zinc soil concentration of 50 ppm.<sup>52</sup> The ( $B_r/B_v$ ) ratio of 0.6 was determined from references 16, 17, 19, 20, 67, 97, 114, and 116. Combining this ratio with the default  $B_v$  value generates a  $B_r = 0.9$ . Examination of Table 2.9 shows that predicted plant concentrations using these default concentration factors fall well within observed ranges.

Figures 2.17 and 2.18 show the default  $B_v$  and ( $B_r/B_v$ ) ratios, respectively, for Period IV transition elements used in the TERRA computer code. The solid lines in the figures show the systematic trends in these parameters defined by the default estimates. The dots represent the parameter values as determined from the geometric means method. The error bars represent one geometric standard deviation. With the exception of chromium, all  $B_v$  default values fall within one standard deviation of the mean. For all elements except nickel, the ( $B_r/B_v$ ) ratio is the geometric mean of the reference values.

### 2.1.7 Period V transition elements

The Period V transition elements contain the controversial and radiologically important element technetium and the toxic metal cadmium. Additionally, this period includes the element ruthenium which is also important radiologically. For concentration factors, cadmium,<sup>16,17,19,20,24,65,97,102,104,105,114,116,124-126</sup> molybdenum,<sup>16,17,19,65,76,120,121</sup> technetium<sup>23,107,122,123,127</sup> and are the best documented, followed by ruthenium<sup>22,59,60,63</sup> and zirconium.<sup>16</sup> No references were found for niobium, rhodium, palladium, and silver.

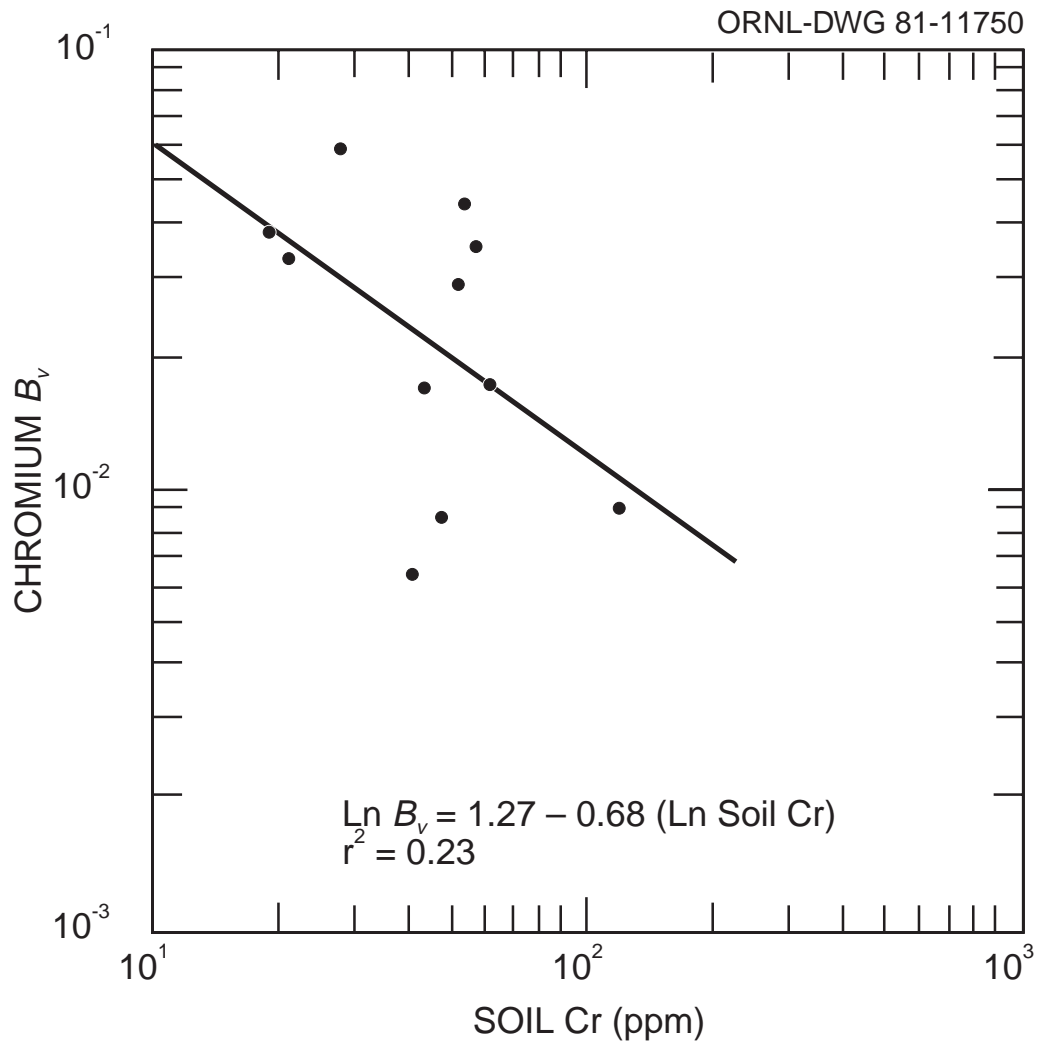


Figure 2.11. Correlation between soil chromium concentration and the soil-to-plant concentration factor,  $B_v$ , for chromium based on references 16 and 65.

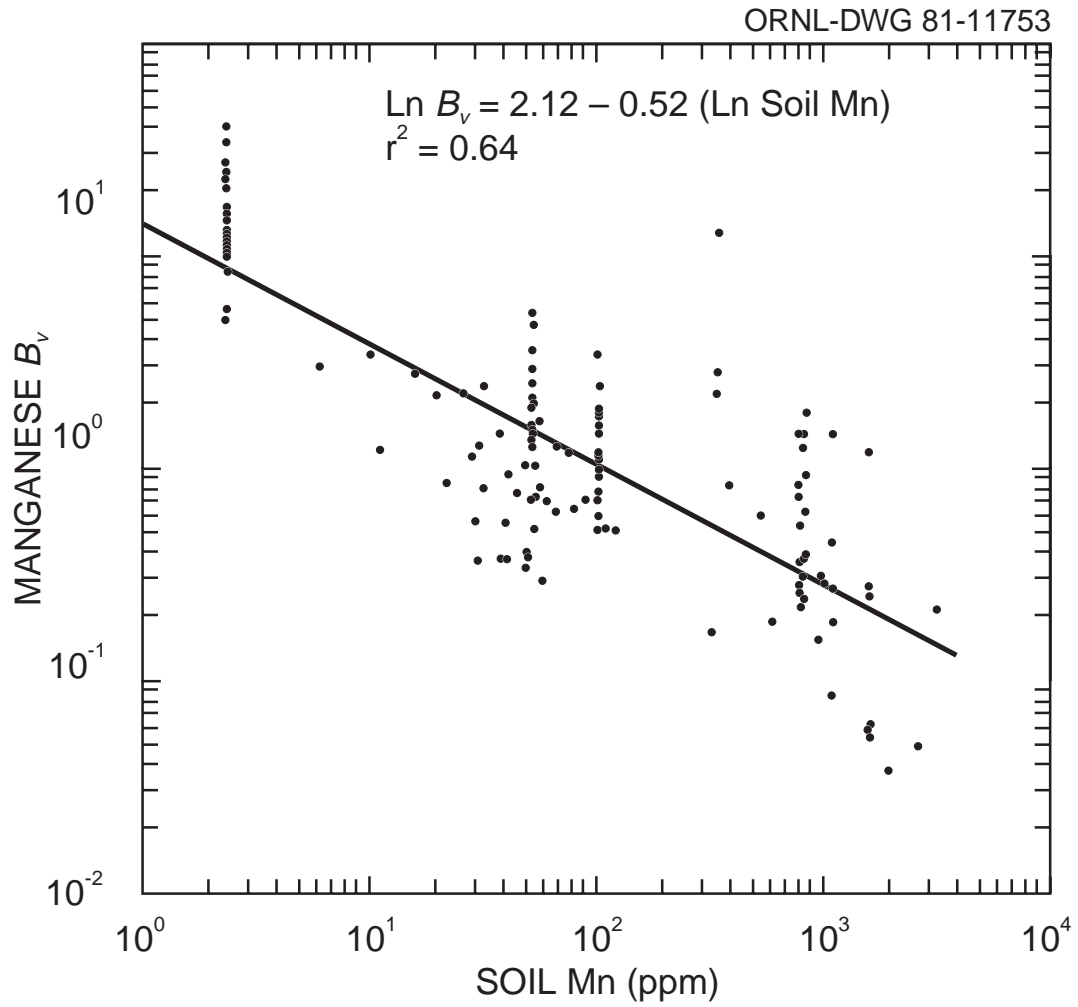


Figure 2.12. Correlation between soil manganese concentration and the soil-to-plant concentration factor,  $B_v$ , for manganese based on references 16, 36, 37, 104, 112, and 113.



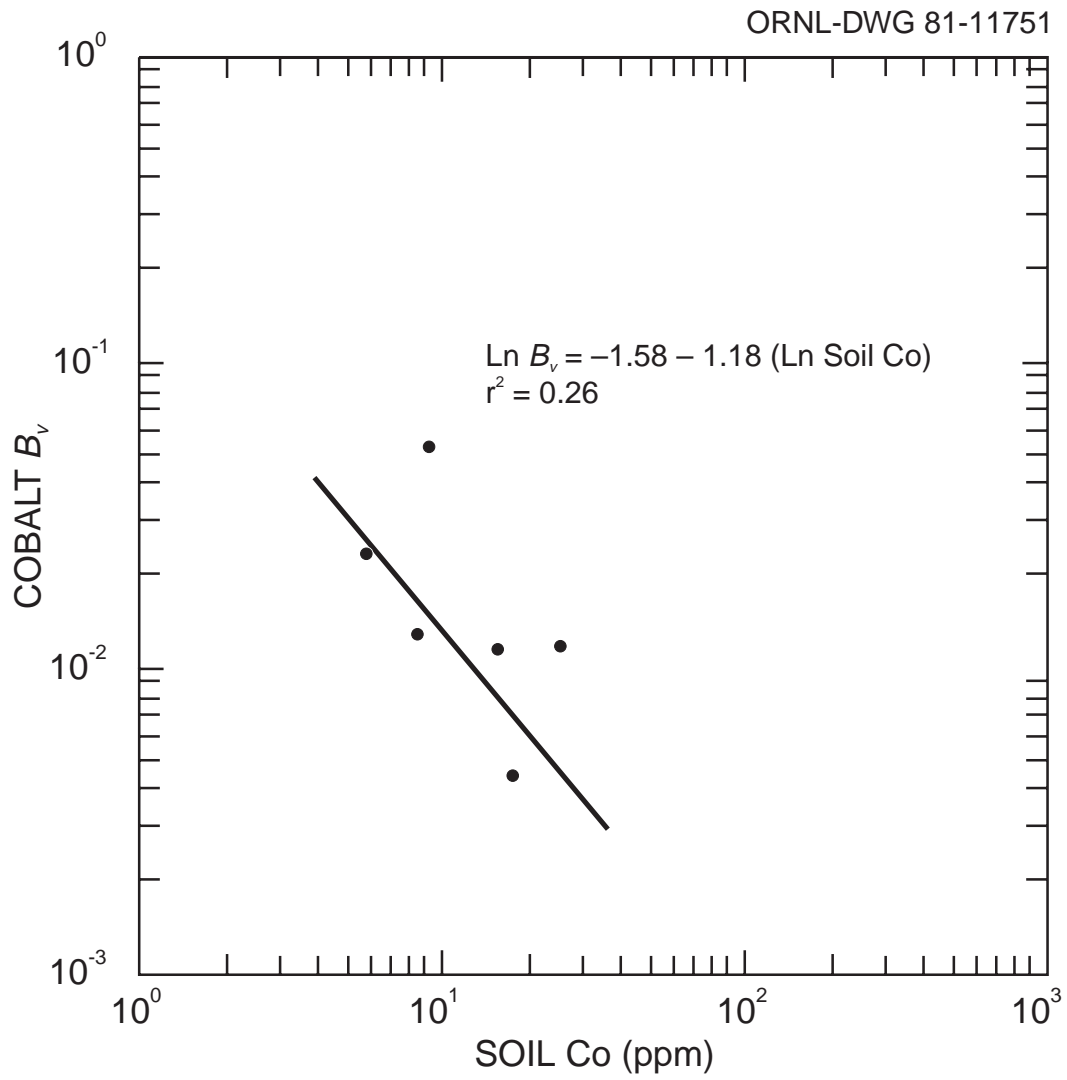


Figure 2.14. Correlation between soil cobalt concentration and the soil-to-plant concentration factor,  $B_v$ , for cobalt based on references 16 and 65.



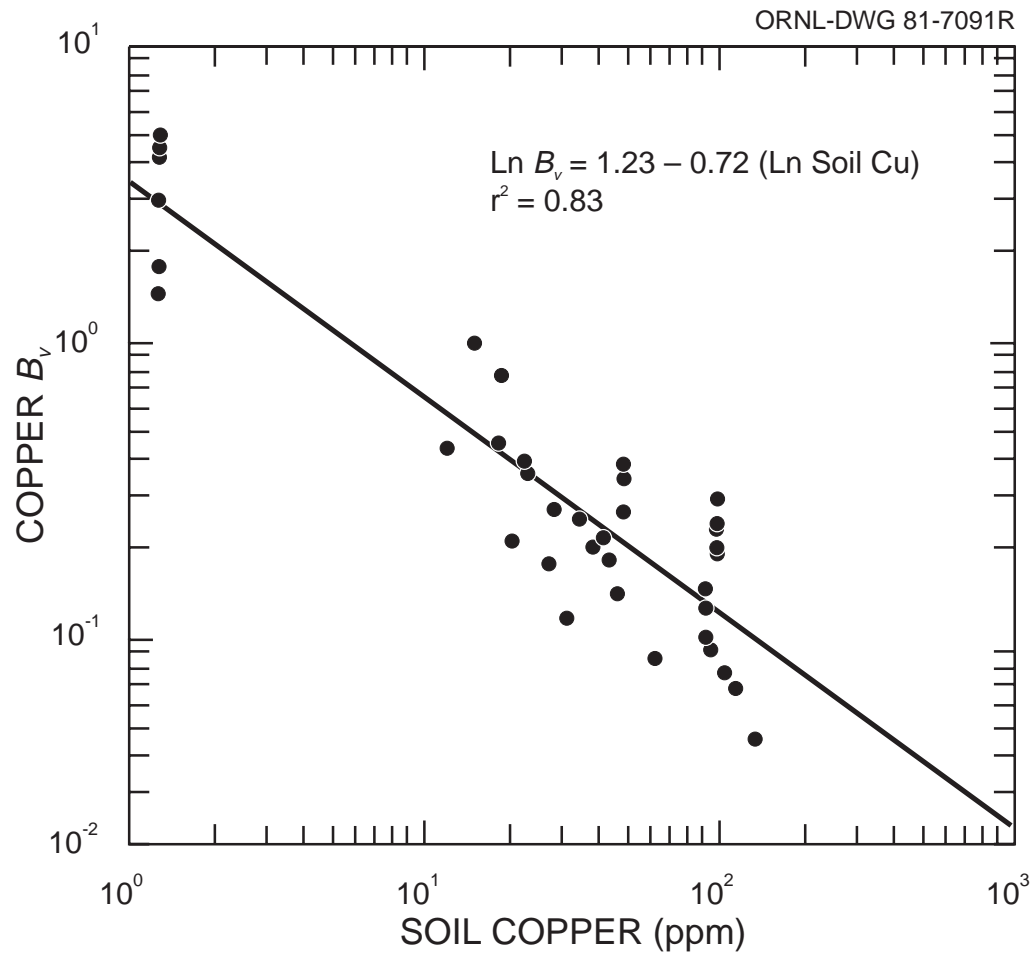


Figure 2.15. Correlation between soil copper concentration and the soil-to-plant concentration factor,  $B_v$ , for copper based on references 16, 104, and 115.

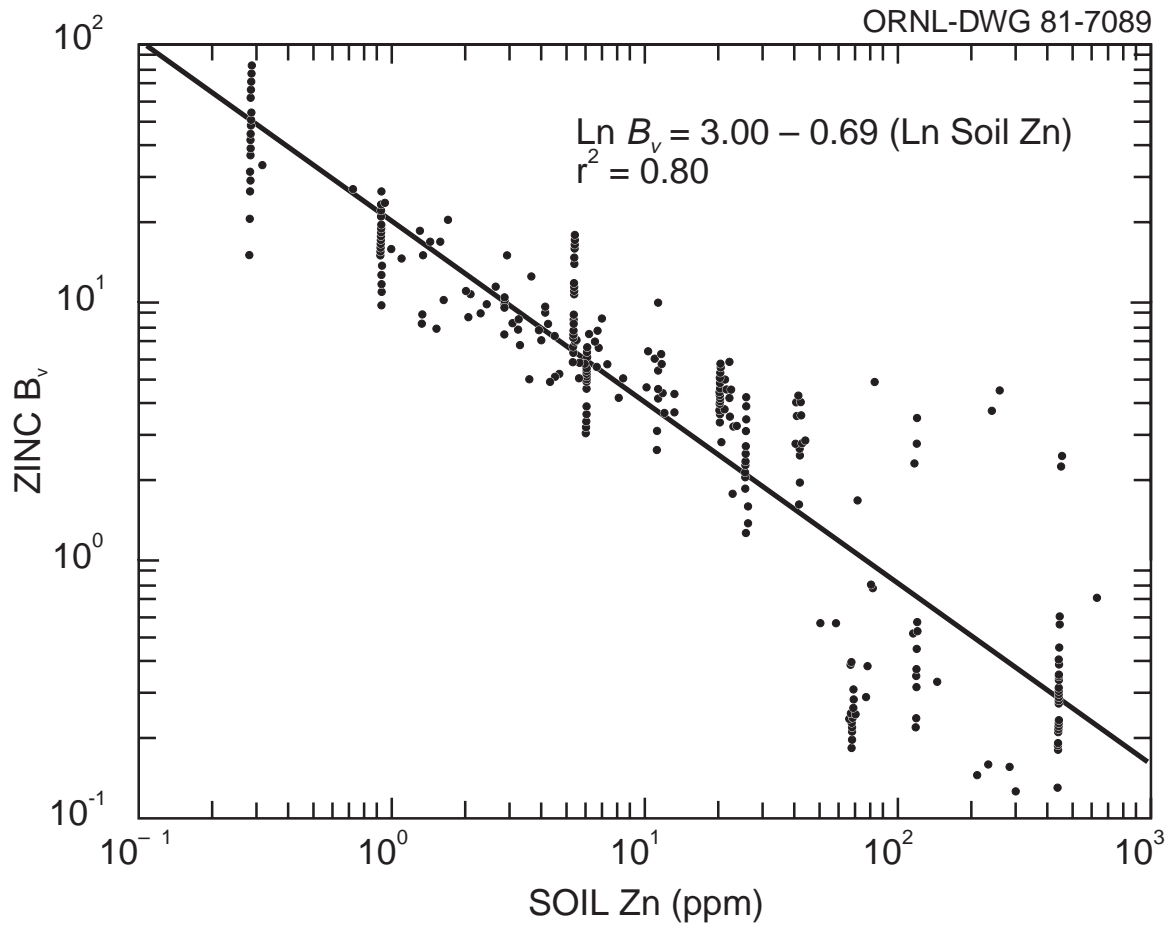


Figure 2.16. Correlation between soil zinc concentration and the soil-to-plant concentration factor,  $B_v$ , for zinc based on references 16, 35, 37, 67, 97, 104, 114, 115, and 119.

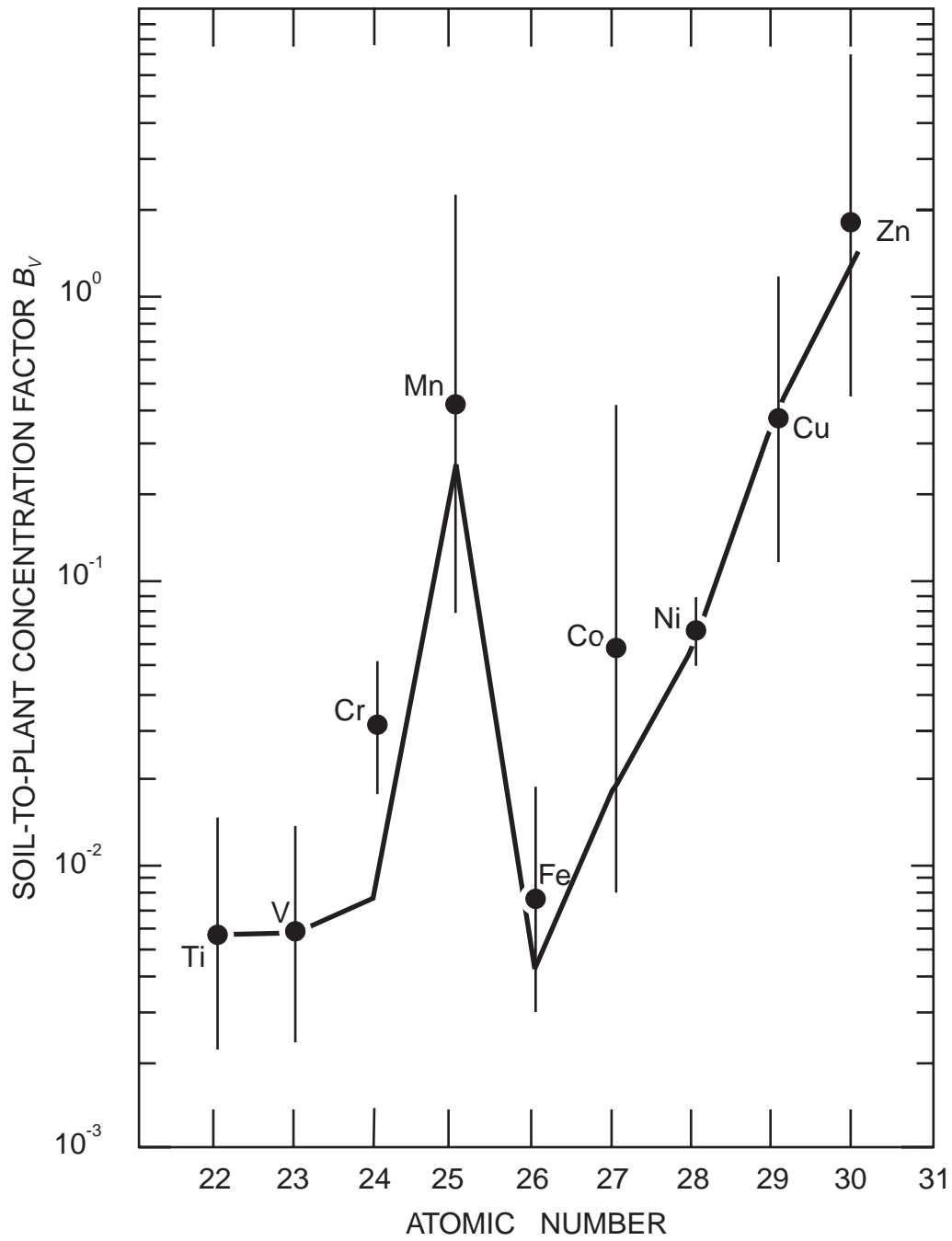


Figure 2.17. Assumed systematic trends in  $B_v$  for Period IV elements based on default  $B_v$  estimates. Solid dots and error bars represent geometric means and standard deviations determined from available references.

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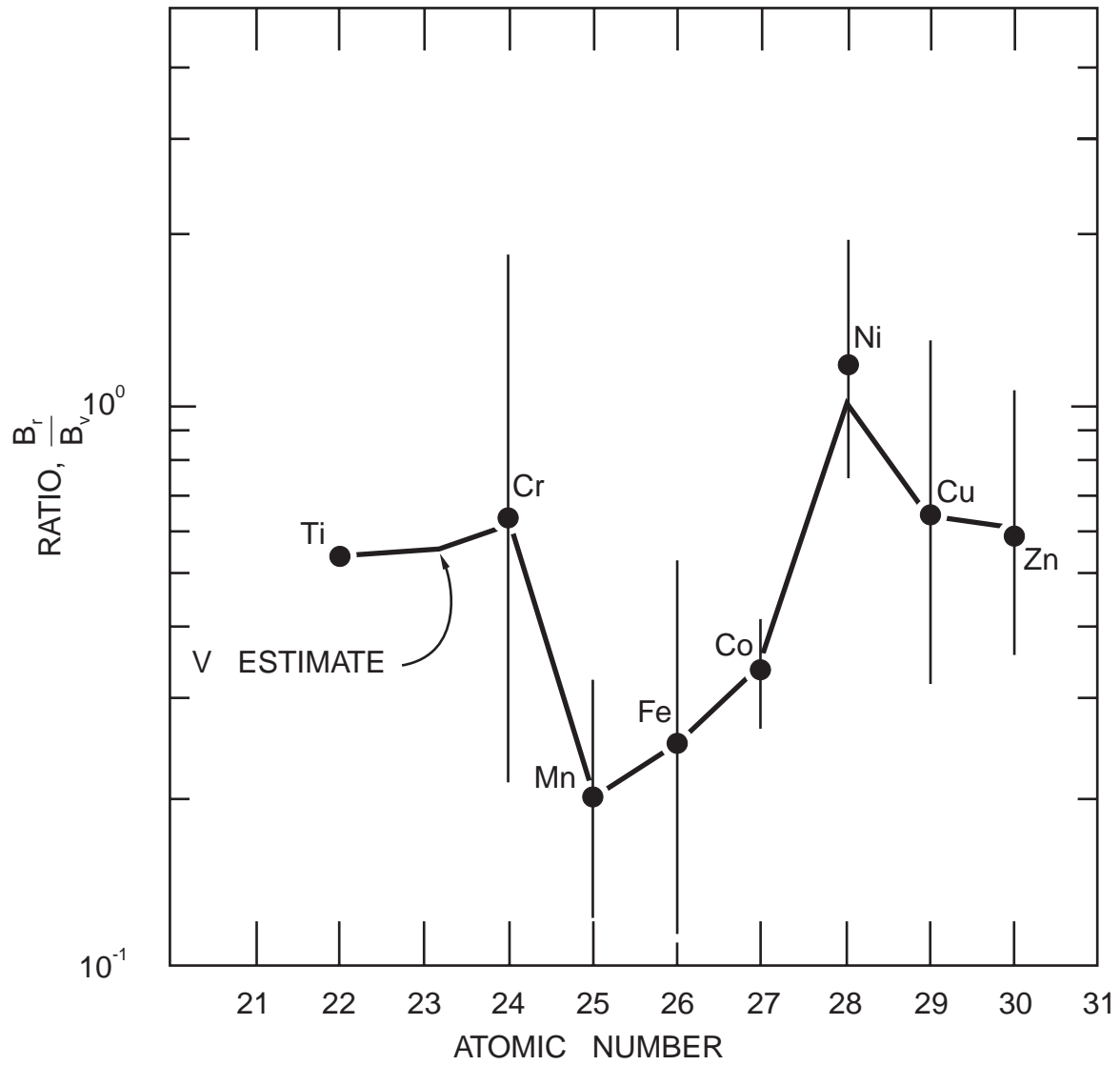


Figure 2.18. Assumed systematic trends in  $(B_r/B_v)$  ratio for Period IV elements. Solid dots and error bars represent geometric means and standard deviations of the mean determined from available references.

Because of its importance radiologically and because of the high concentration factors previously reported for technetium,<sup>23,107,122</sup> it will be given special attention. Hoffman et al.<sup>123</sup> critiqued past studies of technetium uptake using the pertechnetate anion ( $\text{TcO}_4^-$ ) and concluded that the concentration factors of 100-1000 derived from these studies were inappropriate because of the high levels of technetium added to the soils and the measurement of concentration factors before plant maturity. Evidence further suggests that technetium in soil becomes increasingly sorbed and thus is less available for plant uptake with time.<sup>23,128</sup> Aging of soils over 100 days decreased observed concentration ratios by factors of 1.5 to 5.1 in one study by Cataldo.<sup>107</sup> Thus, the application of short-term pot studies to long-term assessments is clearly inappropriate for technetium. Therefore, the concentration factors representing field measurements of long-term technetium uptake in plants reported by Hoffman et al.<sup>123</sup> were adopted for the TERRA code, and references 23, 107, and 122 were used only for calculation of  $B_r$  or were excluded from our analyses.

The geometric mean of the  $B_v$  values reported by Hoffman et al.<sup>123</sup> is 9.5. The geometric mean for  $B_r$  derived from references 23 and 122 is 1.3. This value was rounded to 1.5 for use as a default value in TERRA. The  $(B_r/B_v)$  ratio generated by the two default values is 0.16 which compares favorably with the observed  $(B_r/B_v)$  ratios for molybdenum and ruthenium. It is interesting that a  $B_{iv,2}$  generated from  $B_r$  (see Sect. 2.1) is roughly an order of magnitude less than the value suggested in Moore et al.<sup>1</sup> which takes into account successive harvesting of food crops. No information is available on average technetium concentrations in typical soils and vegetation. Until such information becomes available the  $B_v$  and  $B_r$  for technetium remain suspect.

The  $B_v$  for molybdenum of 0.25 is based on references 16, 65, 76, and 120. Although Singh and Kumar<sup>121</sup> reported soybean grain and leaf molybdenum concentrations from which a  $(B_r/B_v)$  ratio of 2.2 was derived, the  $(B_r/B_v)$  ratio for determination of  $B_r$  was derived from references 16, 17, and 19. This  $(B_r/B_v)$  ratio is 0.25 and yields a  $B_r$  estimate of 0.06. These  $B_v$  and  $B_r$  estimates predict vegetable and produce concentrations which agree well with observed concentrations (Table 2.10).

The  $B_v$  estimate of 0.002 for zirconium is based on the data on pumpkin leaves and vines by Baes & Katz.<sup>16</sup> A value of 0.25 was chosen for the default  $(B_r/B_v)$  ratio for zirconium based on the above analysis for molybdenum. The resultant  $B_r$  estimate of  $5.0 \times 10^{-4}$  yields predicted plant concentrations which are consistent with observed concentrations (Table 2.10). Observed zirconium concentrations in vegetative growth in Table 2.10 are based on a range of values reported for cabbage. Shacklette et al.<sup>53</sup> report that zirconium is "infrequently detected in food plants." Thus, the "observed" plant concentrations in Table 2.10 for zirconium may not be entirely representative of actual produce concentration. Therefore, agreement of observed and predicted concentrations in Table 2.10 was not considered essential to acceptance or rejection of  $B_v$  and  $B_r$  values. Thus, although the predicted  $C_v$  is below the reported  $C_v$  for zirconium the default  $B_v$  for zirconium based on reference 16 is used as default in TERRA.

The  $B_v$  for ruthenium of 0.075 is based on references 22, 59, 60, and 63. The  $(B_r/B_v)$  ratio from references 22, 60, and 63 is 0.26, yielding a  $B_r$  estimate of 0.02. Unfortunately, no estimate of ruthenium in typical soils was available for comparison of observed and predicted plant concentrations.

The occurrence of cadmium in soils and plants has been well studied. The  $B_v$  for cadmium was determined from eleven references (16, 17, 24, 65, 97, 104, 105, 114, and 124-126). The geometric mean of the eleven geometric means is 0.55. A  $(B_r/B_v)$  ratio of 0.26 was derived from references 16, 19, 20, 24, 97, 102, 105, 114, 116, 125, and 126, yielding an estimate of  $B_r = 0.15$ . Agreement between observed and predicted cadmium concentrations in plants is excellent (Table 2.10).

Default values of  $B_v$  and  $B_r$  for niobium, rhodium, palladium, and silver were determined primarily through elemental systematic approaches, because no references on direct determination of  $B_v$  or  $B_r$  for these elements were available. The assumption that Period V transition elements

**Table 2.10. Comparison of observed and predicted concentrations of Period V transition elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Zr	300	53 to 74	0.60	$5.0 \times 10^{-3}$ to 11	0.15
Nb		0.038		0.017	
Mo	2.0	0.35 to 2.9	0.50	0.060 to 13	0.12
Tc					
Ru				$1.0 \times 10^{-4}$ to $4.0 \times 10^{-3}$	
Rh					
Pd					
Ag	0.10	0.13	0.040	0.057	0.010
Cd	0.50	0.13 to 2.4	0.28	0.013 to 0.82	0.075

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

are natural analogs of Period IV transition elements suggested that the ratio of  $B_v$  estimates for these periods might vary systematically from Group IVB to Group IIB. Examination of these ratios for which  $B_v$  estimates had been made via other approaches (Fig. 2.19) yielded estimates of  $B_v$  ratio for Nb/V by linear extrapolation between the Zr/Ti ratio and the Mo/Cr ratio. Likewise the Rh/Co, Pd/Ni, and Ag/Cu ratios were extrapolated from the Ru/Fe and Cd/Zn ratios. These estimated ratios, when multiplied by default  $B_v$  estimates for Period IV elements (Sect. 2.1.6), yielded  $B_v$  estimates for the Period V elements niobium, rhodium, cobalt, palladium, and silver. Plotting of the resultant Period V transition element  $B_v$  estimates by atomic number (Fig. 2.20) yields results somewhat similar to the same plot for Period IV transition elements (Fig. 2.17). Unfortunately, comparison of observed and predicted  $C_v$  and  $C_r$  for niobium, rhodium, and palladium is not possible until more information is available. Some comparison for silver is possible (Table 2.10), although typical silver concentrations in plants are only approximates. The systematics approach seems to underpredict  $B_v$  for silver, but by less than an order of magnitude. The default  $B_r$  estimates for niobium, rhodium, palladium, and silver used in Fig. 2.2 were derived from an assumed ( $B_r/B_v$ ) value of 0.25, which is consistent with observations for molybdenum and cadmium.

### 2.1.8 Period VI transition elements

Very few references for plant uptake of the Period VI transition elements were available. Also, comparisons between observed and predicted produce and plant concentrations were difficult to make because of the uncertainty in typical soil and plant concentrations (Table 2.11). Therefore,  $B_v$  and  $B_r$  default estimates for Period VI transition elements are mostly based on their Period IV and V analogs.

Single measurements of associated soil and plant concentrations applicable to  $B_v$  were found in reference 65 for hafnium, tantalum, and tungsten. Three additional measurements were found in reference 101 for tungsten. The geometric means approach for tungsten indicates a  $B_v$  which is

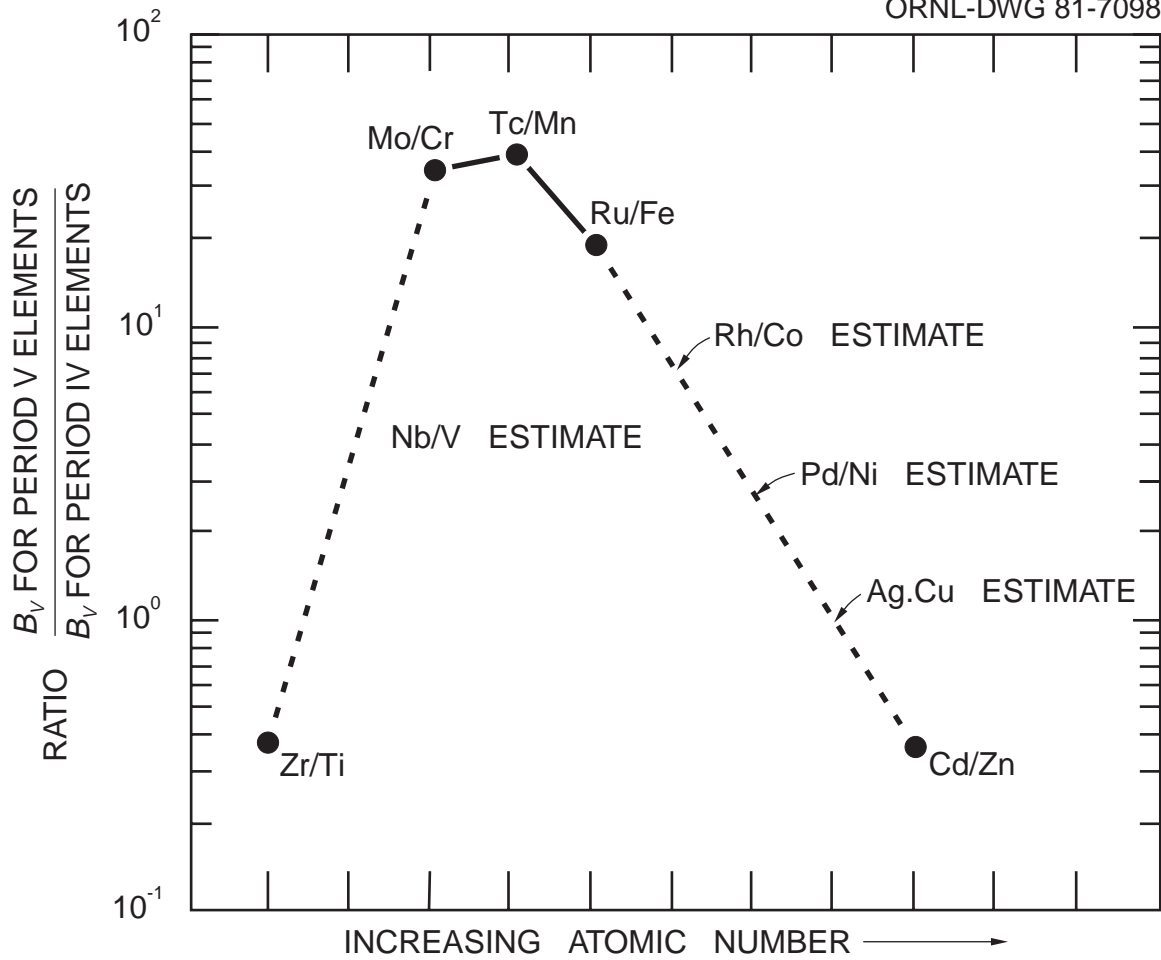


Figure 2.19. Assumed systematic trends in the ratio of  $B_V$  for Period V and IV elements (Nb/V, Rh/Co, Pd/Ni, and Ag/Cu) based on the ratios of default  $B_V$  estimates for other elements in the periods.

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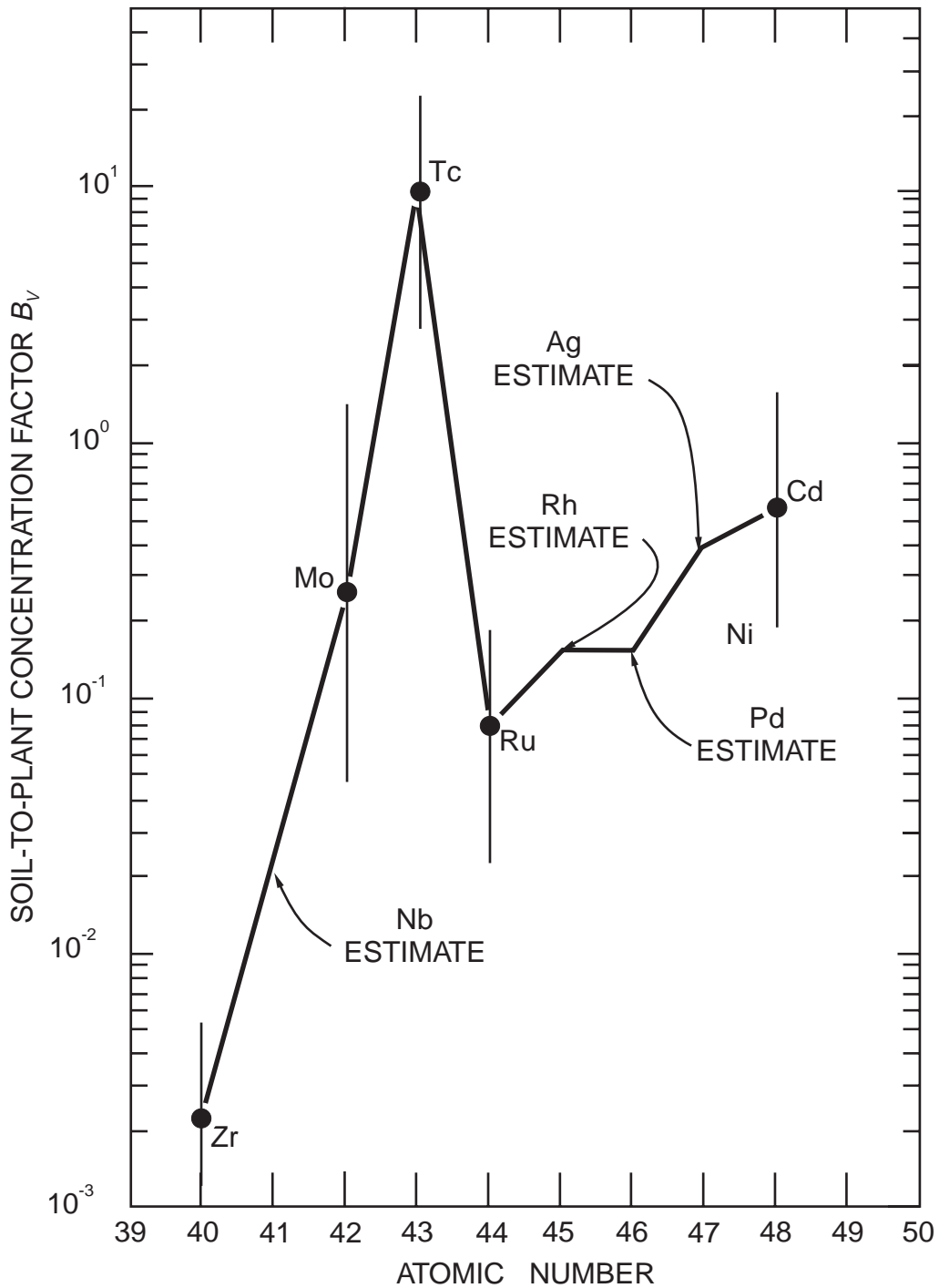


Figure 2.20. Assumed systematic trend in  $B_v$  for Period V transition elements based on default  $B_v$  estimates. Solid dots and error bars represent geometric means and standard deviations determined from available references.



**Table 2.11. Comparison of observed and predicted concentrations of Period VI transition elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Hf	6.0	<6.3×10 <sup>-3e</sup>	0.021	2.3×10 <sup>-3</sup> to 2.0 <sup>e</sup>	5.1×10 <sup>-3</sup>
Ta					
W		0.064		0.029	
Re		6.4×10 <sup>-4</sup>		2.9×10 <sup>-4</sup>	
Os					
Ir					
Pt					
Au		<1.1×10 <sup>-4</sup> to 5.3×10 <sup>-3e</sup>		1.0×10 <sup>-5</sup> to 1.1×10 <sup>-3e</sup>	
Hg	0.010	<0.01 to 0.020	9.0×10 <sup>-3</sup>	<0.010 to 0.020	2.0×10 <sup>-3</sup>

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values in reference 53 assuming ash wt./dry wt. = .128 and .057 for vegetative growth and fruits and tubers, respectively

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

<sup>e</sup>Reference 54.

much greater than that for chromium and more nearly equal to that for molybdenum, although in reference 65 the derived molybdenum  $B_v$  exceeds the derived tungsten  $B_v$  by a factor of approximately three. Comparison of  $B_v$  values derived from reference 65 for hafnium and tantalum with their respective Period IV and V analogs indicates that if the single derived values are appropriate, the Period VI transition element concentration factors exceed those for their Period IV analogs, but are less than their Period V analogs.

While the above observations lend insight into the concentration factors for some Period VI transition elements, concentration factors for the rest must rely on supposition until further experimental evidence is available. Figure 2.21 represents the methodology used in determination of default  $B_v$  estimates for Period VI transition elements. To derive these,  $B_v$  default estimates for Period IV transition elements (Sect. 2.1.6) and Period V transition elements (Sect. 2.1.7) were plotted by increasing atomic number. The default  $B_v$  estimate for the Period VI elements were simply the log-averages of the two other elements within each group rounded to the nearest 0.5 decimal place. This method insures that trends observed in Periods IV and V are generally repeated in Period VI (increasing  $B_v$  for the first four members of the period, decrease in the fifth, etc.). While such repetition of trends may be acceptable if general chemical properties are assumed to be an important basis for  $B_v$  behavior, our method has serious limitations. Our procedure implies that, except for Groups IVB and IIB, Period VI element  $B_v$  values exceed those for Period IV and are exceeded by those for Period V. Such an implication is unfounded and may be a serious limitation to our approach. However, determination of the most appropriate default estimates of  $B_v$  for Period VI transition elements will require direct experimental measurement of them.

There were no available references for the ( $B_r/B_v$ ) ratio or for  $B_r$  for the Period VI elements. Therefore, a value of 0.25 for the ( $B_r/B_v$ ) ratio was assumed, based on analysis of Period V transition elements. This value was used with the default  $B_v$  estimates to generate default  $B_r$  estimates.

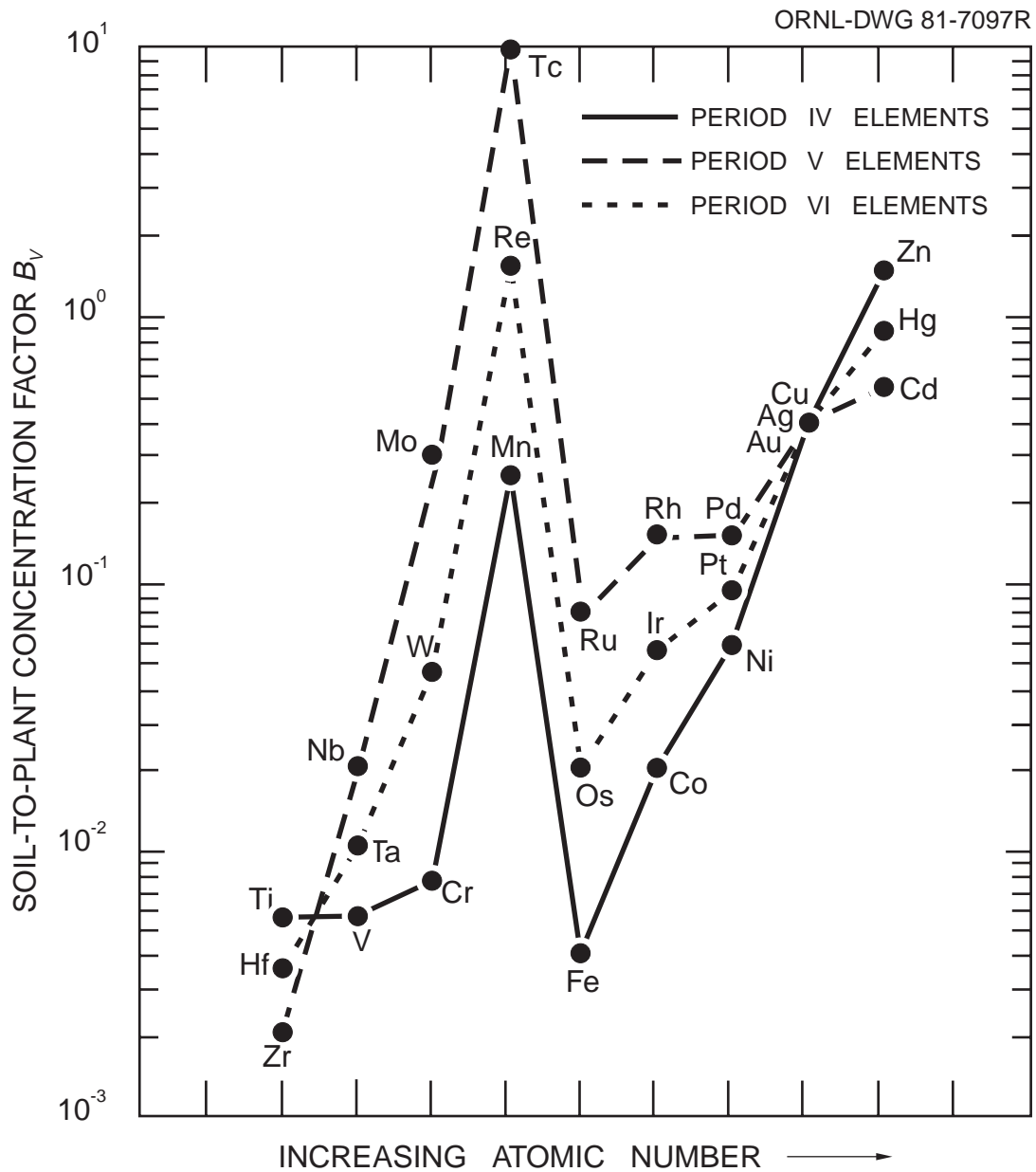


Figure 2.21. Assumed systematic trend in  $B_v$  for Period VI elements based on assumed systematic trends in Period IV and V elements.

Comparisons of observed and predicted plant concentrations were possible only for hafnium and mercury. For these elements predicted values were always within an order of magnitude of the observed ranges. However, observed ranges were usually bounded on the low sides by detection limits of the analysis procedures.<sup>54</sup>

### 2.1.9 The actinide elements

The actinide elements have been extensively studied with respect to plant uptake from soil. The greatest number of references were found for plutonium<sup>8-10,30,59,101,129-138</sup> and americium,<sup>10,30,129,131,133,136,137,139-142</sup> with fewer references for uranium,<sup>29,65,90,91,143</sup> thorium,<sup>65,90,91</sup> neptunium, and curium.<sup>10,30,131</sup> No literature references were found for actinium, protactinium, or any elements of atomic number greater than 96.

The  $B_v$  for plutonium appears to be lognormally distributed and reported values range from  $10^{-6}$  to  $10^{-2}$  (Fig. 2.22). The fourteen references used to determine  $B_v$  for plutonium yielded a geometric mean of  $4.5 \times 10^{-4}$ . The  $(B_r/B_v)$  ratio of 0.1 was calculated from references 8, 10, 30, 129, 130, 134, and 136. This value produces a  $B_r = 4.5 \times 10^{-5}$  which agrees well with the geometric mean of  $B_r$  derived from references 8, 10, 30, 129, 133, 134, 136, and 138. No measurements of typical or average concentrations of plutonium in soils or vegetable produce were available for comparison between predicted and observed concentrations. Comparisons of predicted and observed actinide concentrations were only possible for thorium and uranium (Table 2.12).

The  $B_v$  for americium of 0.0055 was derived from references 10, 30, 129, 131, 136, 137, and 139-142. A  $B_r$  of  $2.5 \times 10^{-4}$  was derived from references 10, 30, 129, and 136 by selecting a value midway between the range defined by the geometric mean of  $B_r$  and the product of the default  $B_v$  estimate and the geometric mean for  $(B_r/B_v)$  ratio.

The  $B_v$  for uranium of 0.0085 was determined from references 29, 65, and 91. The  $(B_r/B_v)$  ratios derived from data reported by Prister<sup>29</sup> and Fedorov and Romanov<sup>143</sup> both equaled a value of 0.5, and this value was used to determine a default  $B_r$  estimate of 0.004. Comparison of predicted and observed vegetable concentrations supports the default concentration factors, although typical uranium concentrations in vegetative portions of produce are unavailable.

The  $B_v$  for thorium of  $8.5 \times 10^{-4}$  was determined from references 65 and 91. No references were available for a thorium  $(B_r/B_v)$  ratio, and thus the value of 0.1 used for radium was assumed, yielding a default  $B_r$  estimate of  $8.5 \times 10^{-5}$ . Comparisons of observed and predicted vegetation concentrations are hampered by the uncertainty in thorium concentrations in vegetation. In the food surveys carried out by Oakes et al.<sup>54</sup> and Monford et al.<sup>144</sup> most thorium concentrations in food items were at or below detection limits. However, it may be concluded that the default  $B_v$  and  $B_r$  estimates assumed here do not overpredict observed food concentrations.

The default  $B_v$  estimates for actinium and protactinium were determined from those of radium and thorium and thorium and uranium, respectively, by assuming systematic variation in  $B_v$  with atomic number in a manner similar to that used for radium and francium (see Sect. 2.1.2). Such a procedure implies that thorium has the lowest  $B_v$  of the actinides of atomic number 89 through 92. This implication has yet to be tested, but examination of our default estimates of the ingestion-to-cow's milk ( $F_m$ ) transfer coefficient shows that it is less than or equal to those for actinium, protactinium, and uranium (see Sect. 2.2 for the milk transfer coefficient). The  $B_r$  for actinium and protactinium was determined by assumption of a  $(B_r/B_v)$  ratio of 0.1 as for radium and thorium.

The  $B_v$  for neptunium of 0.1 is based on references 10, 30, and 131. The  $B_r$  default estimate of 0.01 is based on the geometric means of  $B_r$  values from references 10 and 30. This value suggests that a  $(B_r/B_v)$  ratio of 0.1 is appropriate for neptunium also.

The  $B_v$  for curium of  $8.5 \times 10^{-4}$  is based on references 10, 30, and 141. The  $B_r$  estimate of  $1.5 \times 10^{-5}$  is based on the geometric means of  $B_r$  from references 10 and 30, suggesting an appropriate  $(B_r/B_v)$  ratio of less than 0.1. In the TERRA code  $B_v$  and  $B_r$  estimates for elements of atomic number greater than 96 are set equal to those for curium (element 96).

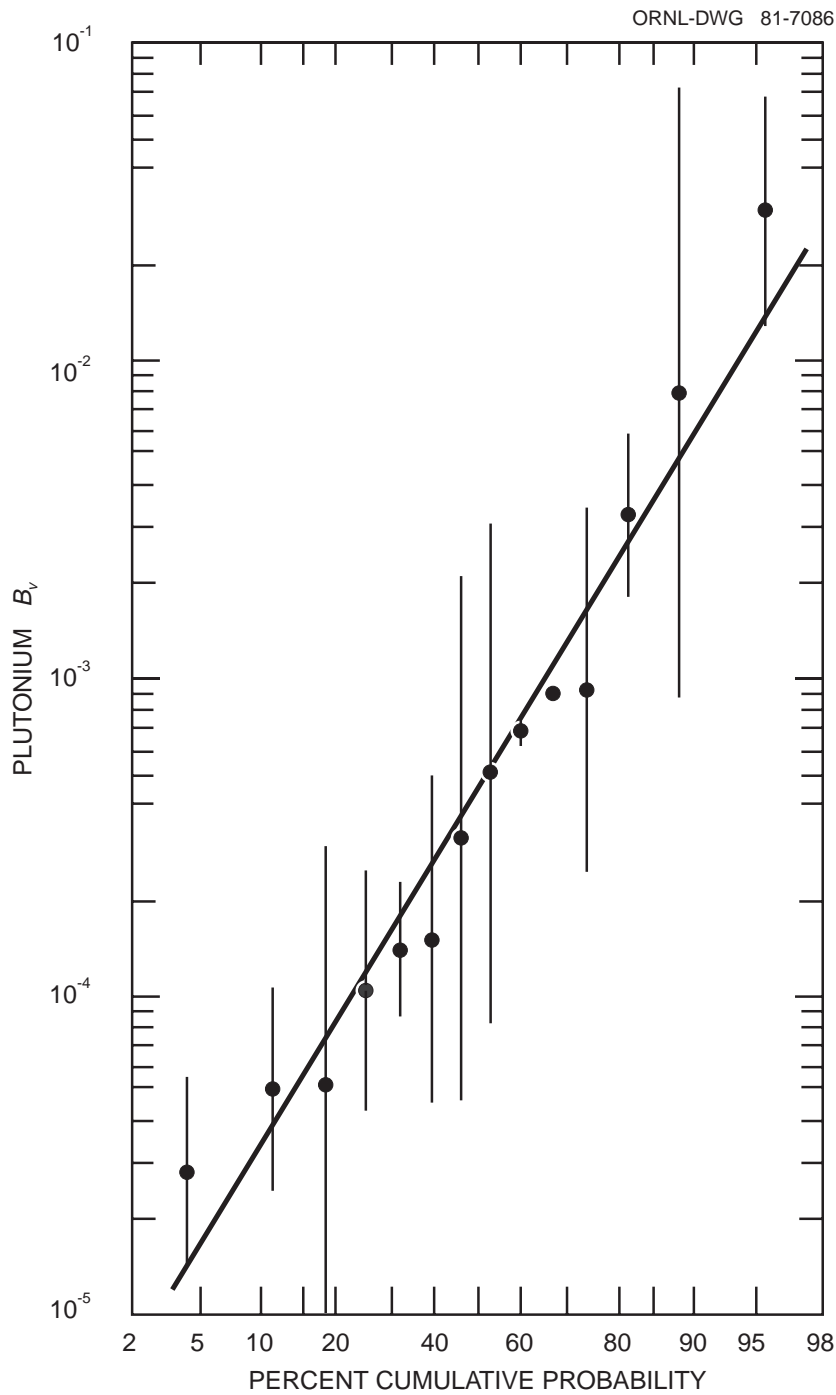


Figure 2.22. Lognormal probability plot of geometric means of  $B_v$  for plutonium (calculated from references 8-10, 30, 59, 101, 129, 131, 132, and 134-138), including one geometric standard deviation of the mean.

**Table 2.12. Comparison of observed and predicted concentrations of actinide elements in produce and plants (ppm, dry wt.)**

Element	Average concentration in soil ( $C_s$ ) <sup>a</sup>	Vegetative growth ( $C_v$ )		Fruits and tubers ( $C_r$ )	
		Observed range <sup>b</sup>	Predicted <sup>c</sup>	Observed range <sup>b</sup>	Predicted <sup>d</sup>
Actinide elements					
Ac					
Th	6.0	<0.032	$5.1 \times 10^{-3}$	$<2.5 \times 10^{-3}$ to 0.12	$5.1 \times 10^{-4}$
Pa					
U	1.0		$8.5 \times 10^{-3}$	$3.8 \times 10^{-4}$ to 0.020	$4.0 \times 10^{-3}$
Np					
Pu					
Am					
Cm					

<sup>a</sup>Reference 52.

<sup>b</sup>Taken or calculated from values reported in reference 144.

<sup>c</sup>The product,  $B_v \times C_s$ .

<sup>d</sup>The product,  $B_r \times C_s$ .

### 2.1.10 Comparison of default estimates with previously published values

Comparisons of our default estimates of  $B_v$  and  $B_r$  with previously used or reported values is difficult because the parameter definitions used here differ somewhat from past soil-plant uptake parameter definitions. However, general comparisons may be made. The most useful comparison is with the soil-to-plant uptake parameter  $B_{iv}$  in Table E-1 of the NRC Reg. Guide 1.109.<sup>6</sup> Most of these values of  $B_{iv}$  were, in turn, taken from reference 15 by dividing the “concentration in terrestrial plants” (Table 10A) by the “elemental composition of typical agricultural soil” (Table 4). In reference 15 the plant concentrations were converted to a wet or fresh weight basis by assuming 25% dry matter in plants. Thus, the  $B_{iv}$  values generated from Tables 10A and 4 may be converted to a dry weight basis by multiplying by a factor of four. The resultant dry weight  $B_{iv}$  values may be directly compared with our  $B_v$  estimates (Fig. 2.23).

In comparing plant uptake parameters it should be remembered that the criteria for  $B_v$  and  $B_{iv}$  definition are comparable, but not equivalent. Also, as evidenced by figures 2.3, 2.7, and 2.22, each default estimate is representative of a distribution of values. Thus, a factor of 2 or 3 difference between  $B_v$  and  $B_{iv}$  should not be considered significant. Therefore, in Fig. 2.23 we have highlighted those elements for which an order of magnitude difference or greater occurs between our numbers and those in reference 15. These elements include fluorine, silicon, calcium, titanium, selenium, strontium, rhodium, palladium, indium, tellurium, osmium, iridium, platinum, gold, thallium, bismuth, polonium, radium, thorium, neptunium, and curium. Our approaches to determination of  $B_v$  estimates have led to lower estimates than those derived from reference 15 for more than half of these elements. For elements calcium, strontium, and neptunium, numerous experimental results indicate higher default values than those derived from reference 15.

## 2.2 Ingestion-to-Milk Parameter, $F_m$

The ingestion-to-milk transfer coefficients for milk cows used in TERRA are representative of the fraction of the daily elemental intake in feed which is transferred to a kilogram of milk. The

	I A	II A											III A	IV A	V A	VI A	VII A
II	Li + 8	Be + 6											B + 5		N		F + 100
III	Na - 3	Mg	III B	IV B	V B	VI B	VII B	VIII		I B	II B	Al + 5	Si + 600	P	S		Cl + 4
IV	K	Ca + 100	Sc	Ti + 25	V	Cr + 7.5	Mn	Fe	Co	Ni	Cu	Zn	Ga + 4	Ge	As	Se - 200	Br - 2
V	Rb - 3.5	Sr + 38	Y	Zr + 3	Nb	Mo - 2	Tc + 9.5	Ru - 3	Rh - 350	Pd - 133	Ag	Cd - 2	In - 250	Sn + 3	Sb + 5	Te - 200	I + 2
VI	Cs + 2	Ba + 7.5		Hf + 5	Ta + 4	W	Re	Os - 13	Ir - 950	Pt - 21	Au + 40	Hg	Tl - 250	Pb - 6	Bi - 17	Po - 1600	At
VII	Fr	Ra + 12															
Lanthanides			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides			Ac - 3	Th - 20	Pa - 4	U	Np + 10	Pu - 2	Am + 5.5	Cm - 12							

Figure 2.23. Comparison of soil-to-plant concentration factor default values reported in this report and derived from reference 15. The “+” and “-” signs indicate whether our estimates are greater or less than, respectively, those derived from reference 15. The values indicated are the difference factor, and circled elements indicate a difference factor of at least an order of magnitude.

elemental values for this parameter (Fig. 2.24) were taken from the extensive review in 1977 by Ng et al.,<sup>145</sup> except for the elements chromium, manganese, iron, nickel, zirconium, antimony, mercury, polonium, and americium which were taken from a later (1979) reference.<sup>40</sup> The protocol for rounding adopted for  $B_v$  and  $B_r$  was used also for  $F_m$ . The error introduced in defining the parameter in days/kilogram (here) rather than days/liter (as by Ng and his associates) is much less than that introduced by the rounding protocol, because the density of milk ranges from 1.028 to 1.035 kg/L.<sup>146</sup>

### 2.3 Ingestion-to-Beef Parameter, $F_f$

The ingestion-to-beef parameters in TERRA are representative of the fraction of the daily elemental intake in feed which is transferred to and remains in a kilogram of beef until slaughter. The elemental values for this parameter (Fig. 2.25) were either taken from several reviews published by Ng and his coworkers<sup>15,39,40</sup> or determined from elemental systematic assumptions. Estimates of  $F_f$  for 32 elements were available from the more recent reviews (references 39 and 40). Values for sodium, phosphorus, potassium, calcium, manganese, iron, zinc, strontium, niobium, antimony, and cerium were taken from reference 40, and values for chromium, cobalt, nickel, copper, rubidium, yttrium, zirconium, molybdenum, technetium, ruthenium, rhodium, silver, tellurium, iodine, cesium, barium, lanthanum, praseodymium, neodymium, tungsten, and americium were taken from reference 39. The  $F_f$  estimates for the remaining elements were derived from reference 15, except for those which exceeded a theoretical maximum value of 1.0 day/kg.

A theoretical maximum  $F_f$  value may be calculated by assuming a 1 unit/kg (wet) concentration of an element in feed. If an extremely conservative 100% efficiency in transfer from feed to muscle is assumed, and beef cattle consume 50 kg (wet) feed per day,<sup>15</sup> and the average muscle mass per head of beef cattle is 200 kg,<sup>13</sup> then the average daily increase in elemental concentration in beef muscle is given by

$$\frac{(1 \text{ unit / kg})(50 \text{ kg / head / day})}{200 \text{ kg beef / head}} = 0.25 \text{ unit / kg beef / day.} \quad (6)$$

Further, if a second extremely conservative assumption that there is no biological turnover of the element from the muscle is made, then assuming that the average beef cow is fed for 200 days before slaughter<sup>13</sup> gives a value of 50 units/kg beef at slaughter. Relating this value to the daily consumption of feed yields a conservative maximum  $F_f$  of (50 units/kg)/(50 units/day) or 1.0 days/kg. Clearly, default estimates near or exceeding this value are highly suspect.

Review of the  $F_f$  values derived from reference 15 indicates that estimates for gallium, germanium, tantalum, polonium, astatine, francium, actinium, thorium, protactinium, neptunium, plutonium, and curium all exceed the above-calculated theoretical maximum. Because of the radiological importance of elements of atomic number greater than 82, a systematic approach based on elemental variation of  $B_v$  and  $F_m$  was used to determine default  $F_f$  estimates (Fig. 2.26). A similar approach using systematic trends observed in  $F_m$  for Period IV elements was used to determine  $F_f$  estimates for gallium and germanium.

The approach used for elements of atomic number greater than 82 was to observe ratios of default  $B_v$  (Fig. 2.1) and  $F_m$  (Fig. 2.24) values for successive elements (Fig. 2.26). The ratios determined for both parameters were log-transformed and averaged. The exponentials of these averages were used to define a default ratio value for successive  $F_f$  default estimates. The  $F_f$  value for americium was then used to determine the default  $F_f$  estimates for curium and plutonium. In turn, each default  $F_f$  estimate was calculated by multiplication with the proper ratio, i.e.,  $\text{Pu } F_f = (\text{Pu/Am}) \text{ ratio} \times (\text{Am } F_f)$ ,  $\text{Np } F_f = (\text{Np/Pu}) \text{ ratio} \times (\text{Pu } F_f)$ , and so on. Implicit in such an argument is the assumption that the availability of an element for plant uptake and transportability to milk is indicative of its availability or transportability to beef. Some support for this argument is

	I A	II A											III A	IV A	V A	VI A	VII A
II	Li 0.020	Be $9.0 \times 10^{-7}$											B $1.5 \times 10^{-3}$		N 0.025		F $1.0 \times 10^{-3}$
III	Na 0.035	Mg $4.0 \times 10^{-3}$	III B	IV B	V B	VI B	VII B	VIII		I B	II B	Al $2.0 \times 10^{-4}$	Si $2.0 \times 10^{-5}$	P 0.015	S 0.015	Cl 0.015	
IV	K $7.0 \times 10^{-3}$	Ca 0.010	Sc $5.0 \times 10^{-6}$	Ti 0.010	V $2.0 \times 10^{-5}$	Cr $1.5 \times 10^{-3}$	Mn $3.5 \times 10^{-4}$	Fe $2.5 \times 10^{-4}$	Co $2.0 \times 10^{-3}$	Ni $1.0 \times 10^{-3}$	Cu $1.5 \times 10^{-3}$	Zn 0.010	Ga $5.0 \times 10^{-5}$	Ge 0.070	As $6.0 \times 10^{-5}$	Se $4.0 \times 10^{-3}$	Br 0.020
V	Rb 0.010	Sr $1.5 \times 10^{-3}$	Y $2.0 \times 10^{-5}$	Zr $3.0 \times 10^{-5}$	Nb 0.020	Mo $1.5 \times 10^{-3}$	Tc 0.010	Ru $6.0 \times 10^{-7}$	Rh 0.010	Pd 0.010	Ag 0.020	Cd $1.0 \times 10^{-3}$	In $1.0 \times 10^{-4}$	Sn $1.0 \times 10^{-3}$	Sb $1.0 \times 10^{-4}$	Te $2.0 \times 10^{-4}$	I 0.010
VI	Cs $7.0 \times 10^{-3}$	Ba $3.5 \times 10^{-4}$		Hf $5.0 \times 10^{-6}$	Ta $3.0 \times 10^{-6}$	W $3.0 \times 10^{-4}$	Re $1.5 \times 10^{-3}$	Os $5.0 \times 10^{-3}$	Ir $2.0 \times 10^{-6}$	Pt $5.0 \times 10^{-3}$	Au $5.5 \times 10^{-6}$	Hg $4.5 \times 10^{-4}$	Tl $2.0 \times 10^{-3}$	Pb $2.5 \times 10^{-4}$	Bi $5.0 \times 10^{-4}$	Po $3.5 \times 10^{-4}$	At 0.010
VII	Fr 0.020	Ra $4.5 \times 10^{-4}$															

Lanthanides	La $2.0 \times 10^{-5}$	Ce $2.0 \times 10^{-5}$	Pr $2.0 \times 10^{-5}$	Nd $2.0 \times 10^{-5}$	Pm $2.0 \times 10^{-5}$	Sm $2.0 \times 10^{-5}$	Eu $2.0 \times 10^{-5}$	Gd $2.0 \times 10^{-5}$	Tb $2.0 \times 10^{-5}$	Dy $2.0 \times 10^{-5}$	Ho $2.0 \times 10^{-5}$	Er $2.0 \times 10^{-5}$	Tm $2.0 \times 10^{-5}$	Yb $2.0 \times 10^{-5}$	Lu $2.0 \times 10^{-5}$
Actinides	Ac $2.0 \times 10^{-5}$	Th $5.0 \times 10^{-6}$	Pa $5.0 \times 10^{-6}$	U $6.0 \times 10^{-4}$	Np $5.0 \times 10^{-6}$	Pu $1.0 \times 10^{-7}$	Am $4.0 \times 10^{-7}$	Cm $2.0 \times 10^{-5}$							

Key: 

Li	—	Symbol
0.020	—	Transfer Coefficient, $F_m$

Figure 2.24. Values of the ingestion-to-milk transfer coefficient  $F_m$  adopted as default estimates in the computer code TERRA.



	I A	II A										III A	IV A	V A	VI A	VII A	
II	Li 0.010	Be $1.0 \times 10^{-3}$										B $8.0 \times 10^{-4}$		N 0.075		F 0.15	
III	Na 0.055	Mg $5.0 \times 10^{-3}$	III B	IV B	V B	VI B	VII B	VIII		I B	II B	Al $1.5 \times 10^{-3}$	Si $4.0 \times 10^{-5}$	P 0.055	S 0.10	Cl 0.080	
IV	K 0.020	Ca $7.0 \times 10^{-4}$	Sc 0.015	Ti 0.030	V $2.5 \times 10^{-3}$	Cr $5.5 \times 10^{-3}$	Mn $4.0 \times 10^{-4}$	Fe 0.020	Co 0.020	Ni $6.0 \times 10^{-3}$	Cu 0.010	Zn 0.10	Ga $5.0 \times 10^{-4}$	Ge 0.70	As $2.0 \times 10^{-3}$	Se 0.015	Br 0.025
V	Rb 0.015	Sr $3.0 \times 10^{-4}$	Y $3.0 \times 10^{-4}$	Zr $5.5 \times 10^{-3}$	Nb 0.25	Mo $6.0 \times 10^{-3}$	Tc $8.5 \times 10^{-3}$	Ru $2.0 \times 10^{-3}$	Rh $2.0 \times 10^{-3}$	Pd $4.0 \times 10^{-3}$	Ag $3.0 \times 10^{-3}$	Cd $5.5 \times 10^{-4}$	In $8.0 \times 10^{-3}$	Sn 0.080	Sb $1.0 \times 10^{-3}$	Te 0.015	I $7.0 \times 10^{-3}$
VI	Cs 0.020	Ba $1.5 \times 10^{-4}$		Hf $1.0 \times 10^{-3}$	Ta $6.0 \times 10^{-4}$	W 0.045	Re $8.0 \times 10^{-3}$	Os 0.40	Ir $1.5 \times 10^{-3}$	Pt $4.0 \times 10^{-3}$	Au $8.0 \times 10^{-3}$	Hg 0.25	Tl 0.040	Pb $3.0 \times 10^{-4}$	Bi $4.0 \times 10^{-4}$	Po $9.5 \times 10^{-5}$	At 0.010
VII	Fr $2.5 \times 10^{-3}$	Ra $2.5 \times 10^{-4}$															
Lanthanides	La $3.0 \times 10^{-4}$	Ce $7.5 \times 10^{-4}$	Pr $3.0 \times 10^{-4}$	Nd $3.0 \times 10^{-4}$	Pm $5.0 \times 10^{-3}$	Sm $5.0 \times 10^{-3}$	Eu $5.0 \times 10^{-3}$	Gd $3.5 \times 10^{-3}$	Tb $4.5 \times 10^{-3}$	Dy $5.5 \times 10^{-3}$	Ho $4.5 \times 10^{-3}$	Er $4.0 \times 10^{-3}$	Tm $4.5 \times 10^{-3}$	Yb $4.0 \times 10^{-3}$	Lu $4.5 \times 10^{-3}$		
Actinides	Ac $2.5 \times 10^{-5}$	Th $6.0 \times 10^{-6}$	Pa $1.0 \times 10^{-5}$	U $2.0 \times 10^{-4}$	Np $5.5 \times 10^{-5}$	Pu $5.0 \times 10^{-7}$	Am $3.5 \times 10^{-6}$	Cm $3.5 \times 10^{-6}$									

Key:	Li 0.010	— Symbol	— Transfer Coefficient, $F_f$
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Figure 2.25. Values of the ingestion-to-beef transfer coefficient  $F_f$  adopted as default estimates in the computer code TERRA.

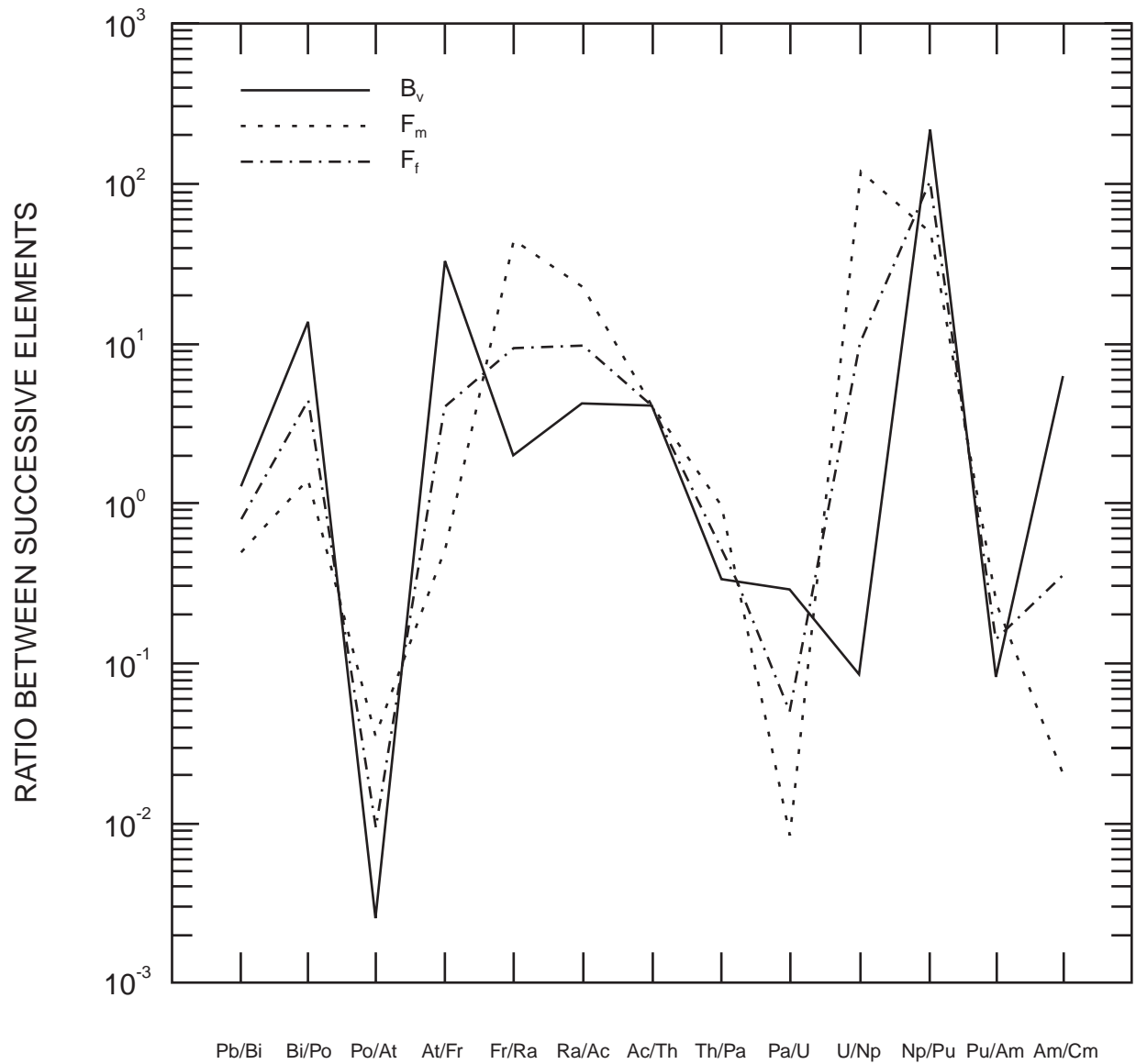


Figure 2.26. Systematic trends in the ratio of default estimates for  $B_v$  and  $F_m$  for successive elements and corresponding assumed ratios for  $F_f$  for successive elements used to determine default  $F_f$  estimates.

seen in the systematic variability of our  $B_v$  estimates (Figs. 2.27 and 2.28) and  $F_m$  estimates (Figs. 2.29 and 2.30). However, experimental determination of  $F_f$  for elements of atomic number greater than 82 would be preferable to our present approach, if available.

#### 2.4 The Distribution Coefficient, $K_d$

The distribution coefficient,  $K_d$  is the ratio of elemental concentration in soil to that in water in a soil-water system at equilibrium. In general,  $K_d$  is measured in terms of gram weights of soil and milliliter volumes of water. In TERRA the distribution coefficient is used in the following equation to determine a location-specific leaching constant for elemental removal from a given soil depth,

$$\lambda_l = \frac{P + I - E}{\theta d [1 + (\frac{\rho}{\theta} K_d)]} \quad (7)$$

where

- $P$  = annual average total precipitation (cm),
- $E$  = annual average evapotranspiration (cm),
- $I$  = annual average irrigation (cm),
- $d$  = depth of soil layer from which leaching occurs (cm),
- $\rho$  = soil bulk density ( $\text{g}/\text{cm}^3$ ),
- $\theta$  = volumetric water content of the soil [ $\text{mL}(=\text{cm}^3)/\text{cm}^3$ ], and
- $K_d$  = the distribution coefficient ( $\text{mL}/\text{g}$ ).

Default estimates of  $K_d$  used in the TERRA code are presented in Fig. 2.31. The mantissa of these values has been rounded off to the nearest 0.5 decimal place as for the other element specific transport parameters. The values for magnesium, potassium, calcium, manganese, iron, cobalt, copper, zinc, strontium, yttrium, molybdenum, technetium, ruthenium, cesium, lead, polonium, cerium, thorium, uranium, neptunium, plutonium, americium, and curium were determined through a review of the  $K_d$  literature. The estimates for the remaining elements were determined by a correlation of  $K_d$  with  $B_v$ . Because of the inherent uncertainties in estimates of  $K_d$  for various materials, a brief discussion of the parameter and its determination is appropriate.

##### 2.4.1 Variability in $K_d$

The first source of variability in the parameter is associated with the laboratory methods used to determine  $K_d$ . Generally, the two most common techniques for determination of  $K_d$  are the column and batch methods, although other methods have been employed to measure distributions of chemical forms<sup>147</sup> or distribution among soil fractions.<sup>148</sup> In the column method a solution of material in water is applied to a column containing uniformly packed soil. The  $K_d$  of the material is determined from comparison of the 50% breakthrough curves for the water and material according to the equation

$$\frac{V_i}{V_w} = \frac{1}{1 + \frac{\rho}{\theta} K_d}, \quad (8)$$

where

- $V_i$  = the velocity of the migrating material (determined from the 50% breakthrough curve) and
- $V_w$  = the velocity of the water.

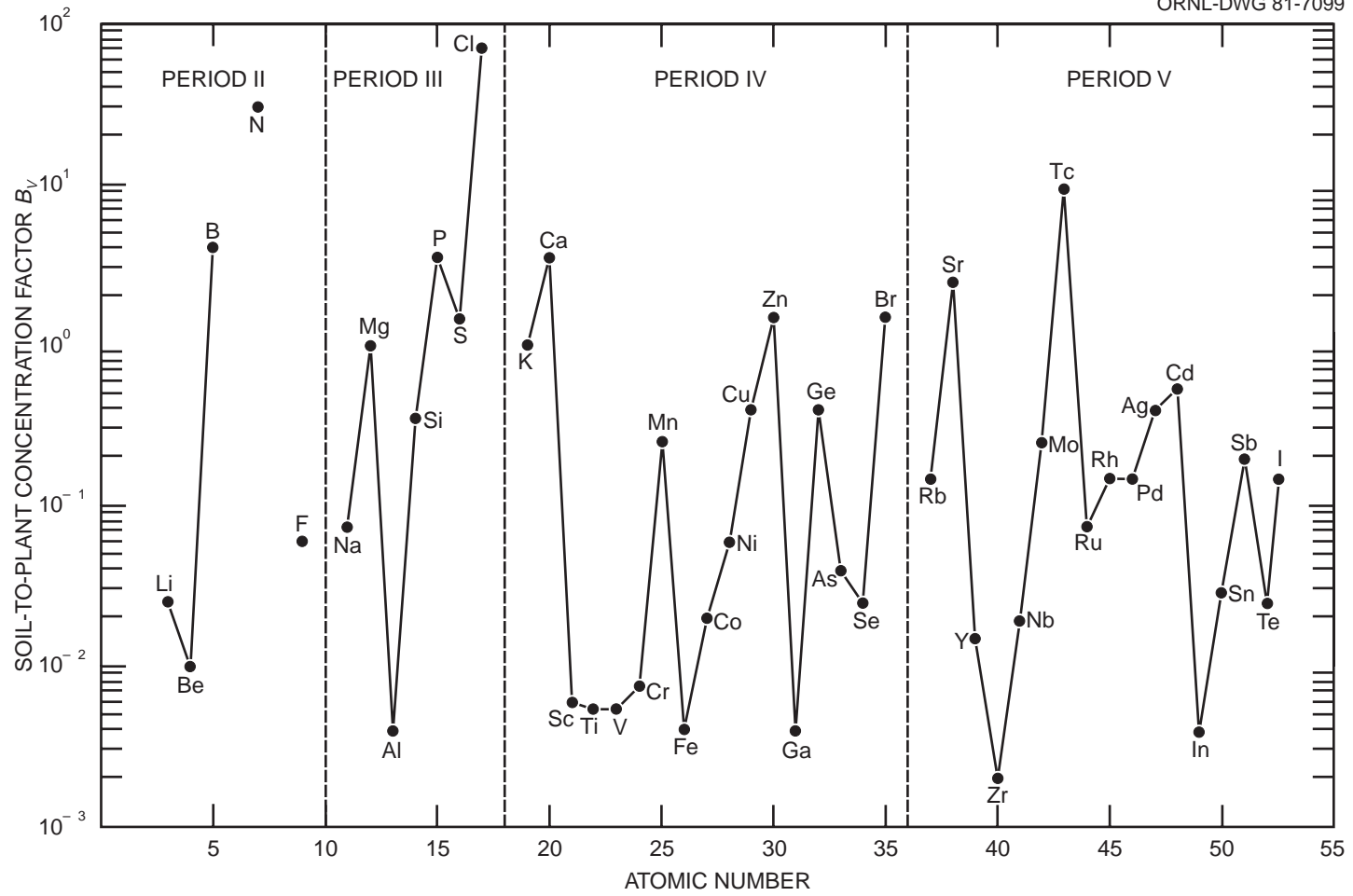


Figure 2.27. Systematic variations in default  $B_v$  estimates for Period II, III, IV, and V elements.

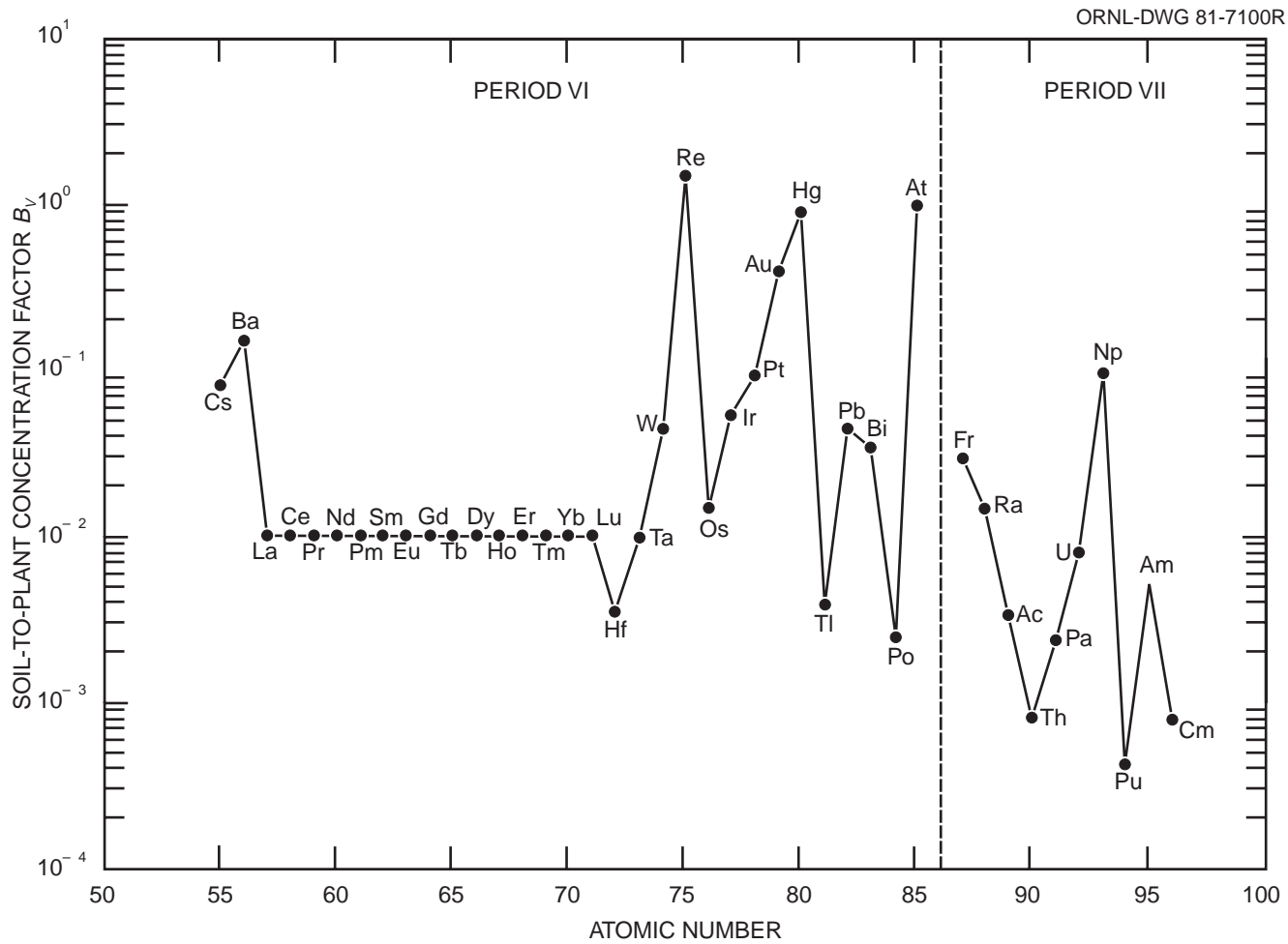


Figure 2.28. Systematic variations in default  $B_v$  estimates for Period VI and VII elements.

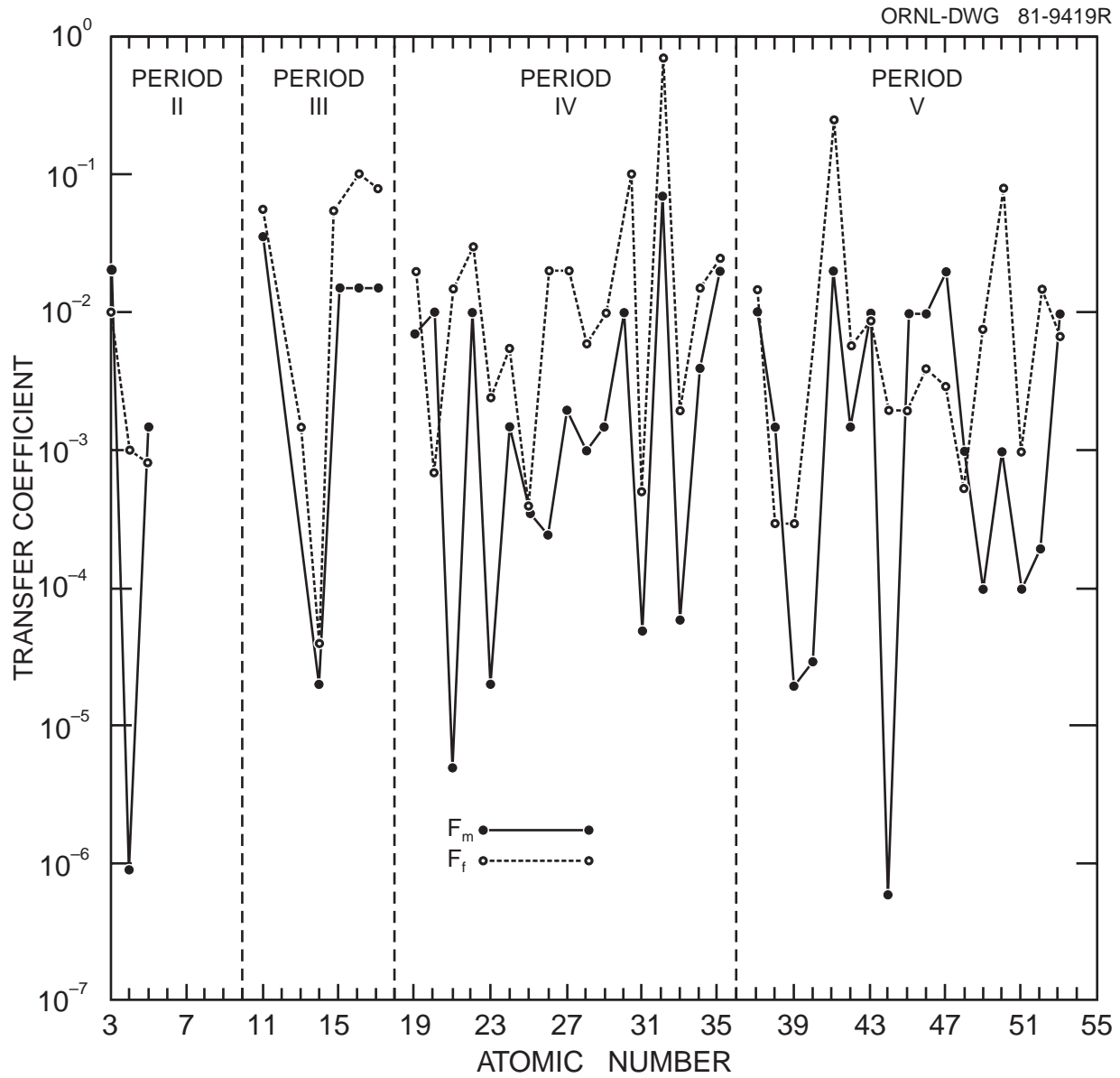


Figure 2.29. Systematic variations in default  $F_m$  and  $F_f$  estimates for Period II, III, IV, and V elements.

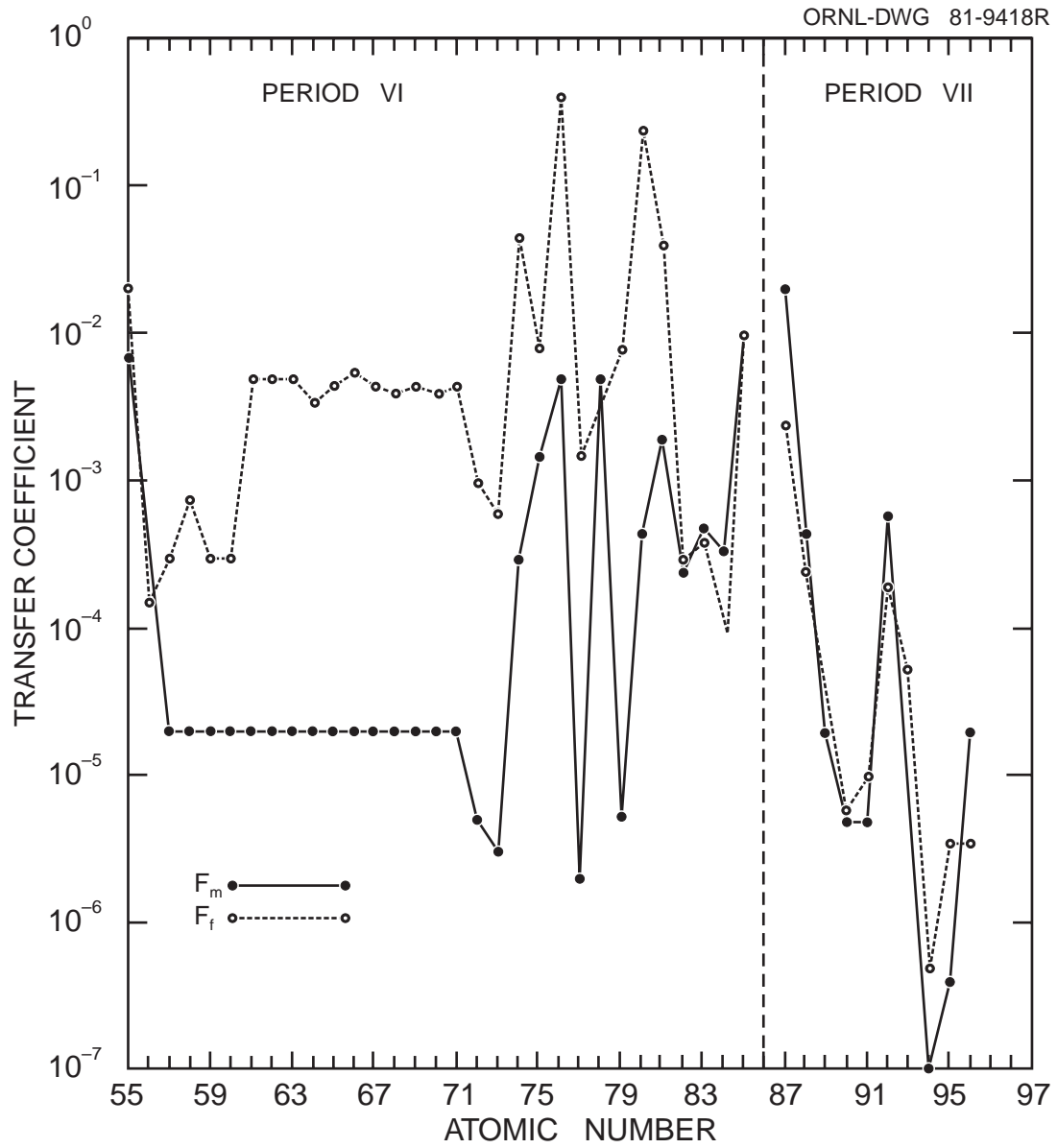


Figure 2.30. Systematic variations in default  $F_m$  and  $F_f$  estimates for Period VI and VII elements.

	I A	II A											III A	IV A	V A	VI A	VII A
II	Li 300	Be 650											B 3.0		N 0.50		F 150
III	Na 100	Mg 4.5	III B	IV B	V B	VI B	VII B	VIII		I B	II B		Al 1500	Si 30	P 3.5	S 7.5	Cl 0.25
IV	K 5.5	Ca 4.0	Sc 1000	Ti 1000	V 1000	Cr 850	Mn 65	Fe 25	Co 45	Ni 150	Cu 35	Zn 40	Ga 1500	Ge 25	As 200	Se 300	Br 7.5
V	Rb 60	Sr 35	Y 500	Zr 3000	Nb 350	Mo 20	Tc 1.5	Ru 350	Rh 60	Pd 60	Ag 45	Cd 6.5	In 1500	Sn 250	Sb 45	Te 300	I 60
VI	Cs 1000	Ba 60		Hf 1500	Ta 650	W 150	Re 7.5	Os 450	Ir 150	Pt 90	Au 25	Hg 10	Tl 1500	Pb 900	Bi 200	Po 500	At 10
VII	Fr 250	Ra 450															

Lanthanides	La 650	Ce 850	Pr 650	Nd 650	Pm 650	Sm 650	Eu 650	Gd 650	Tb 650	Dy 650	Ho 650	Er 650	Tm 650	Yb 650	Lu 650
Actinides	Ac 1500	Th $1.5 \times 10^5$	Pa 2500	U 450	Np 30	Pu 4500	Am 700	Cm 2000							

Key: 

Li 300
-----------

 Symbol  
 Transfer Coefficient,  $K_d$

Figure 2.31. Values of the soil-water distribution coefficient  $K_d$  adopted as default estimates in the computer code TERRA.



In the batch method, soil and water are shaken with the material for a period of time until equilibrium distribution between soil and water is achieved or assumed. Because of nonequilibrium or the influences of convection and diffusion in the column method, these two techniques may give different results for nonionic elemental forms.<sup>149</sup> Thus, in searching the literature for  $K_d$  values, various biases and confounding factors inherent in the laboratory methods used to determine  $K_d$  are reflected in the values reported.

A second factor responsible for variation or imprecision in  $K_d$  measurement is a result of the parameter being a ratio of two concentrations. A small amount of error in measurement of either the soil or water concentration of material may produce a large amount of error in the resultant ratio. For example, in a batch-type experimental system of 10 g soil, 100 mL H<sub>2</sub>O, and 100 µg of material for which the true  $K_d$  is 190 mL/g, a 1% overestimate of the soil concentration (95.95 µg in soil) yields a  $K_d$  of 237 mL/g, or approximately a 25% overestimate of  $K_d$ . The relative error in  $K_d$  estimate from a given percent error in measurement of soil concentration increases rapidly with increasing  $K_d$  (Fig. 2.32). The same is true with a given percent underestimate of the water concentration as the true  $K_d$  of the material decreases. Thus, if an investigator measures only one fraction of the soil-water system and determines the concentration of the other fraction by default, significant errors may be introduced into the  $K_d$  estimate from very small experimental errors of measurement. This magnification of experimental error undoubtedly contributes a significant amount of variability to  $K_d$  estimates for materials which are highly soluble or insoluble.

A third source of variability in  $K_d$  is its variation with soil type. Soils with different pH, clay content, organic matter content, free iron and manganous oxide contents, or particle size distributions will likely yield different  $K_d$  values. For example, in a study by Griffin and Shimp<sup>150</sup> of lead absorption by clay minerals, pH was shown to be an extremely important determinant of  $K_d$ . From their data, an exponential relationship between  $K_d$  and pH of the clays was found. At pH > 7.0, lead  $K_d$  is on the order of 10<sup>3</sup>, and below this pH,  $K_d$  ranges from 10<sup>1</sup> to 10<sup>2</sup>. Soil pH has also been shown to influence  $K_d$  for plutonium and curium;<sup>151-153</sup> ruthenium, yttrium, zirconium, niobium, and cerium;<sup>154</sup> arsenic and selenium;<sup>155,156</sup> and manganese, iron, zinc, cobalt, copper, cadmium, and calcium.<sup>157-159</sup>

Another source of variation in  $K_d$  is the time factor involved with its determination. Batch-type  $K_d$  determinations are usually made over a period of a few to several hours until equilibrium is achieved or assumed. If equilibrium does not occur within this short time period, some error is introduced. Errors from nonequilibrium  $K_d$  determinations made after 24 hours, however, are relatively insignificant.<sup>151,152,160</sup> A more significant error may be introduced by using short term  $K_d$  determinations to simulate leaching over time periods of months or years. Gast et al.<sup>23</sup> found that sorption of Tc-99 by low organic soils tended to significantly increase over a 5-6 week period. Treatments of the soil with dextrose, H<sub>2</sub>O<sub>2</sub>, and steam sterilization, and sorption variation with temperature—all indicated that microbiota played either a direct or indirect role in sorption. Heterotrophic bacteria capable of solubilizing PbS, ZnS, and CdS have been reported by Cole,<sup>161</sup> and microbial influences on the solubility of transuranics has also been suggested by Wildung and Garland.<sup>162</sup> If microbial action is, indeed, important over the long term, then the applicability of  $K_d$  experiments carried out with oven dried and sieved soil to models of leaching in agricultural soils over long time periods must be questioned.

An analysis of the literature was performed to ascertain appropriate distributions of  $K_d$  for various elements (Table 2.13). Because of the variation of  $K_d$  with soil pH, an analysis of 222 agricultural soils<sup>163,164</sup> was used to determine a typical range of pH for agricultural soils. In these soils, pH was found to be normally distributed with a mean pH of 6.7 and 95% of the values between a pH of 4.7 to 8.7. Thus, the criterion was adopted of discarding  $K_d$  values which were measured in soils outside of the pH range of 4.5 to 9. The  $K_d$  determinations used to generate Table 2.13 represent a diversity of soils, pure clays (pure minerals were excluded), extracting solutions (commonly H<sub>2</sub>O, CaCl<sub>2</sub>, or NaCl), laboratory techniques, and magnification of experimental error. Also, unavoidably, single measurements have been combined with replicates, means, and means of means to derive  $K_d$  distributions. When many references have been used to

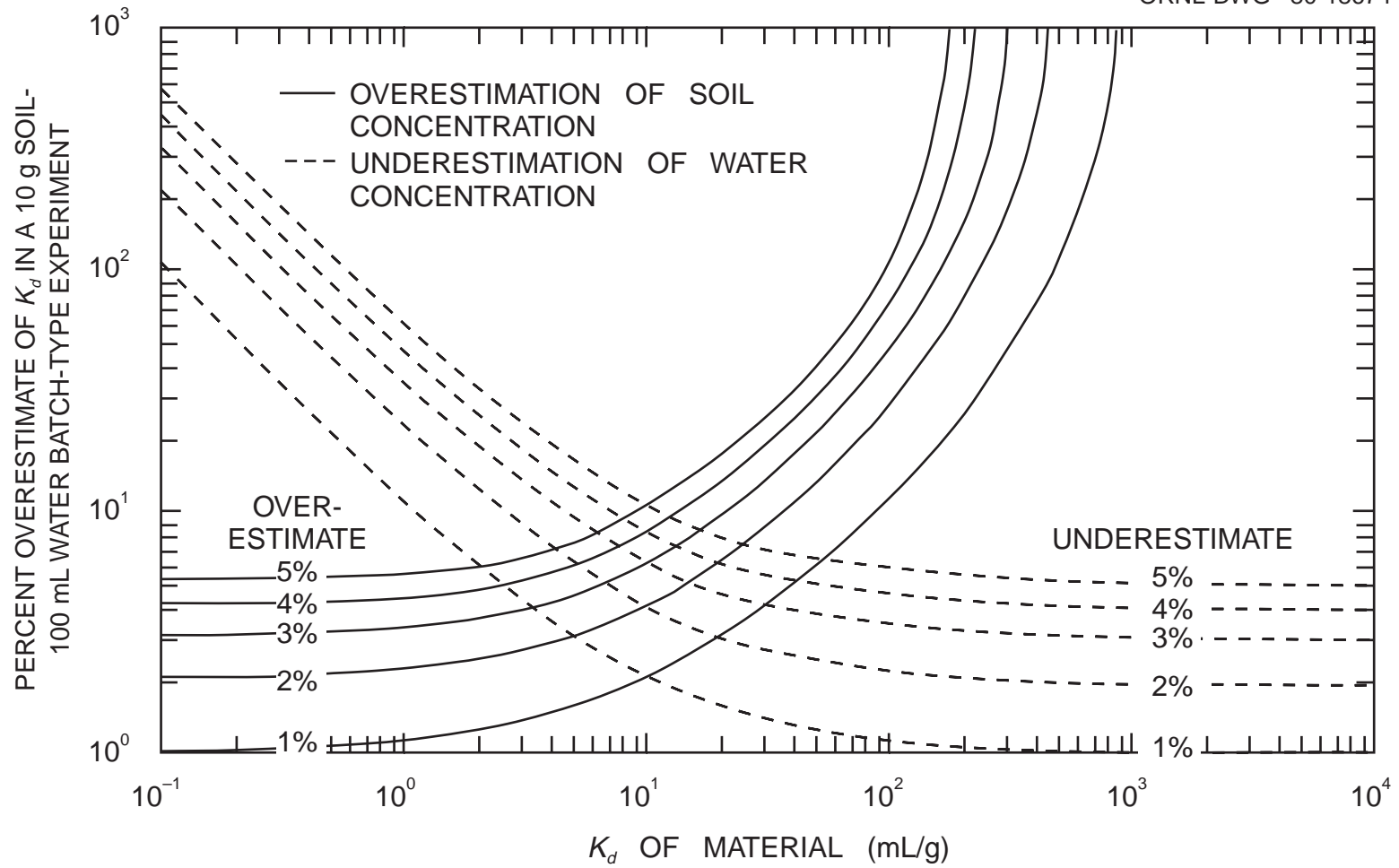


Figure 2.32. Percent error in  $K_d$  estimation from one to five percent overestimates of soil concentration or underestimates of water concentration in a 10 g-100 mL batch-type  $K_d$  experiment.

**Table 2.13. Estimates of the distribution of  $K_d$  for various elements in agricultural soils of pH 4.5 to 9.0**

Element	# Obs.	$\mu^a$	$\sigma^b$	Exp( $\mu$ ) <sup>c</sup>	Observed range <sup>b</sup>	References
					— mL/g —	
Mg	58	1.5	0.40	4.6	1.6 to 13.5	165, 166
K	10	1.7	0.49	5.6	2.0 to 9.0	165
Ca	10	1.4	0.78	4.1	1.2 to 9.8	165
Mn	45	4.2	2.5	65	0.2 to 10,000	149, 158, 167, 168
Fe	30	3.2	2.0	25	1.4 to 1,000	149, 158, 167, 169
Co	57	3.9	1.1	47	0.2 to 3,800	149, 158, 160, 167, 169–171
Cu	55	3.6	0.97	35	1.4 to 333	157, 158
Zn	146	3.6	1.8	38	0.1 to 8,000	149, 157–159, 167
Sr	218	3.6	1.6	37	0.15 to 3,300	149, 152, 154, 160, 167, 169, 171–180
Y	2	6.2	1.7	510	160 to 1,640	154
Mo	17	2.9	2.2	18	0.37 to 400	149
Tc	24	-3.4	1.1	0.033	0.0029 to 0.28	23
Ru	17	5.9	0.75	350	48 to 1,000	154, 160
Ag	16	3.8	1.5	46	10 to 1,000	149, 167
Cd	28	1.9	0.86	6.4	1.26 to 26.8	157
Cs	135	6.9	1.8	1,000	10 to 52,000	149, 160, 167, 169, 171, 173, 175, 177, 178, 180–183
Ce	16	6.7	0.54	840	58 to 6,000	154, 160
Pb	125	6.0	2.1	400	4.5 to 7,640	150, 184
Po	6	6.3	0.65	520	196 to 1,063	184
Th	17	12	0.57	150,000	2,000 to 510,000	185–187
U	24	6.1	2.5	450	10.5 to 4,400	185–187
Np	44	3.4	2.5	29	0.16 to 929	148, 186, 188, 189
Pu	40	8.4	2.4	4,500	11 to 300,000	151, 152–154, 177, 182, 186, 187, 189
Am	46	6.5	2.4	680	1.0 to 47,230	148, 188–190
Cm	31	7.6	1.6	1,900	99.3 to 51,900	148, 153, 189

<sup>a</sup>The mean of the logarithms of the observed values.

<sup>b</sup>The standard deviation of the logarithms of the observed values.

<sup>c</sup>Geometric mean (50% cumulative probability).

generate the distribution, greater assurance can be given that the distribution is a representative distribution because it is not heavily biased by one or two experimental designs or techniques. Where a single or a few references were used, less assurance can be given.

On the basis of distributions computed for cesium and strontium (Fig. 2.33), a lognormal distribution for  $K_d$  has been assumed for all elements. Thus, the median value of the assumed lognormal distribution is used as a best estimate default  $K_d$  for TERRA (except for lead, and technetium where judgement was exercised). However, if the distribution of  $K_d$  computed for cesium and strontium are typical, then  $K_d$  may vary by as much as three orders of magnitude in soils of pH 4.5 to 9.0. Such variation in  $K_d$  is greater than or equal to the variation in  $B_v$  observed for cesium, strontium, and plutonium (Figs. 2.3, 2.7, and 2.22) and suggests the advisability of using site-specific values when available.

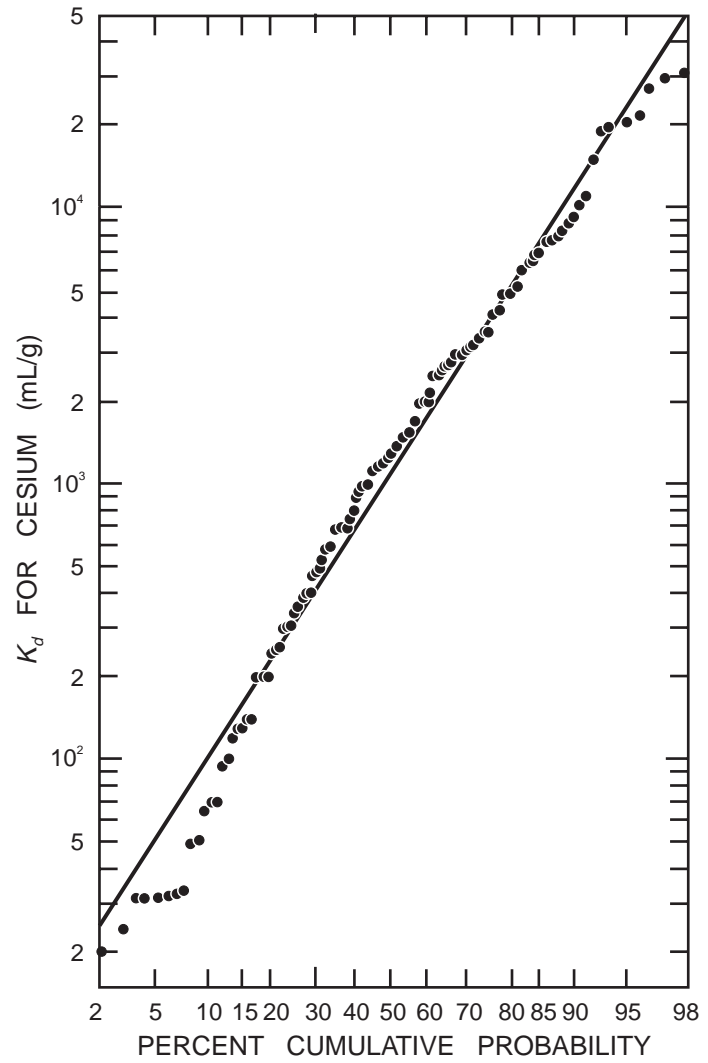
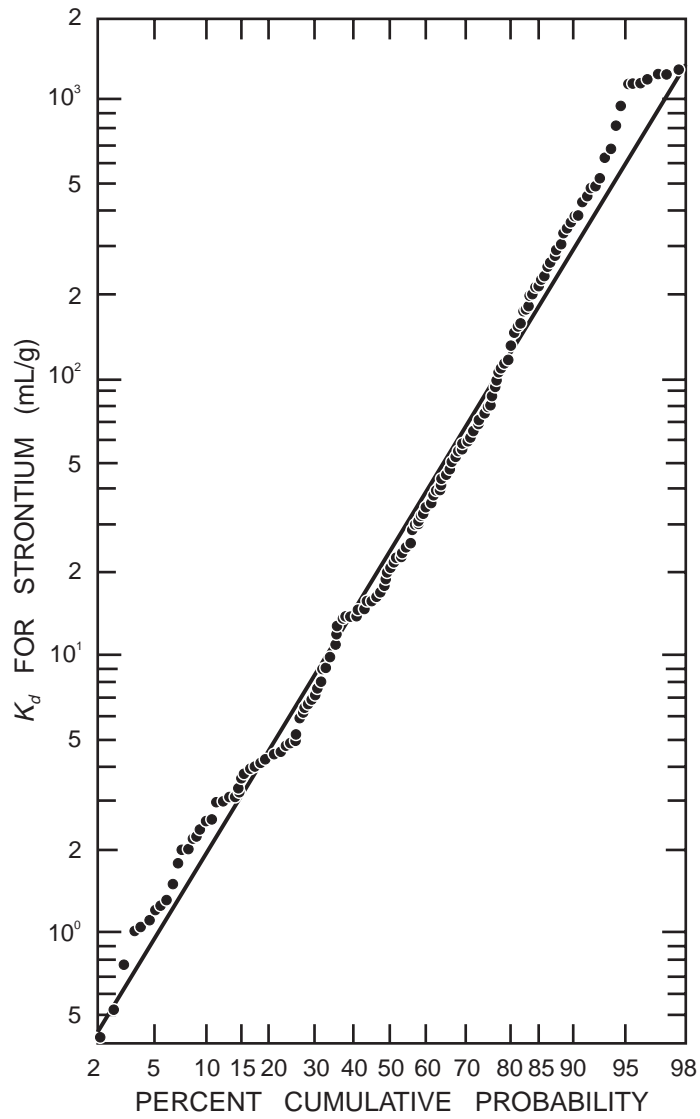


Figure 2.33. Lognormal probability plots of  $K_d$  for cesium and strontium in soils of pH 4.5 to 9 based on available references.

### 2.4.2 Estimates of $K_d$ based on default $B_v$ values

Although  $K_d$  estimates for the 23 above-mentioned elements are subject to great uncertainty, they are based on values reported in the literature. No references are immediately available for the remaining elements of the periodic table. In order to provide a default estimate for these elements, an alternative method is used. In 1979, Van Dorp, Eleveld, and Frissel<sup>191</sup> proposed a model for estimation of the soil-plant concentration factor. Their approach was to calculate the solubility of a nuclide in soil water, its ability to transfer across root membranes, and its upward movement with the transpiration stream. They reasoned that measured values of  $K_d$ , root selectivity coefficient ( $S$ ), and transpiration coefficient ( $T_c$ ) would allow them to predict the soil-plant concentration factor from soil-radionuclide concentration. Their model has not become generally used or accepted for dose calculations, but their implied dependency of  $B_v$  on  $K_d$  is the basis of our approach for estimating default  $K_d$  estimates in lieu of experimental determinations.

Our approach is to presume that the default  $K_d$  estimates for elements in Sect. 2.4.1 and their corresponding  $B_v$  estimates represent a wide variety of soils and plants. Therefore, a single default estimate for  $B_v$  and  $K_d$  will reflect soils, plants, and experimental conditions which are “averaged” or “generalized.” Thus, any relationship observed between  $K_d$  and  $B_v$  may be used to predict “average” or “generalized”  $K_d$  estimates from our default  $B_v$  estimates.

Figure 2.34 shows the correlation found between  $B_v$  and  $K_d$ . It should be noted that the  $B_v$  estimates in Fig. 2.34 are the geometric means determined directly through analysis of reviewed literature, and not necessarily the default values from Fig. 2.1. Technetium is an example. The technetium  $B_v$  of 89 is the geometric mean of the geometric means of references 23, 107, 122, and 123. It was felt that although the short-term plant uptake studies represented in references 23, 107, and 122 were inappropriate for long-term  $B_v$  estimates, they were appropriately associated with the short-term  $K_d$  determinations for technetium (because  $B_v$  decreases and  $K_d$  increases with time). Thus, these two short-term parameters were used in the definition of the  $B_v$ - $K_d$  relationship. However, in Fig. 2.31 we used our best estimate of technetium  $B_v$  and the regression equation

$$K_d = \exp(2.38 - 0.89(\ln B_v)) \quad (9)$$

to determine our best estimate of technetium  $K_d$  of 1.5. In addition to technetium the  $K_d$  default estimates for elements not mentioned in Sect. 2.4.1 were determined via Eq. (9) and the best estimate  $B_v$  default values in Fig. 2.1.

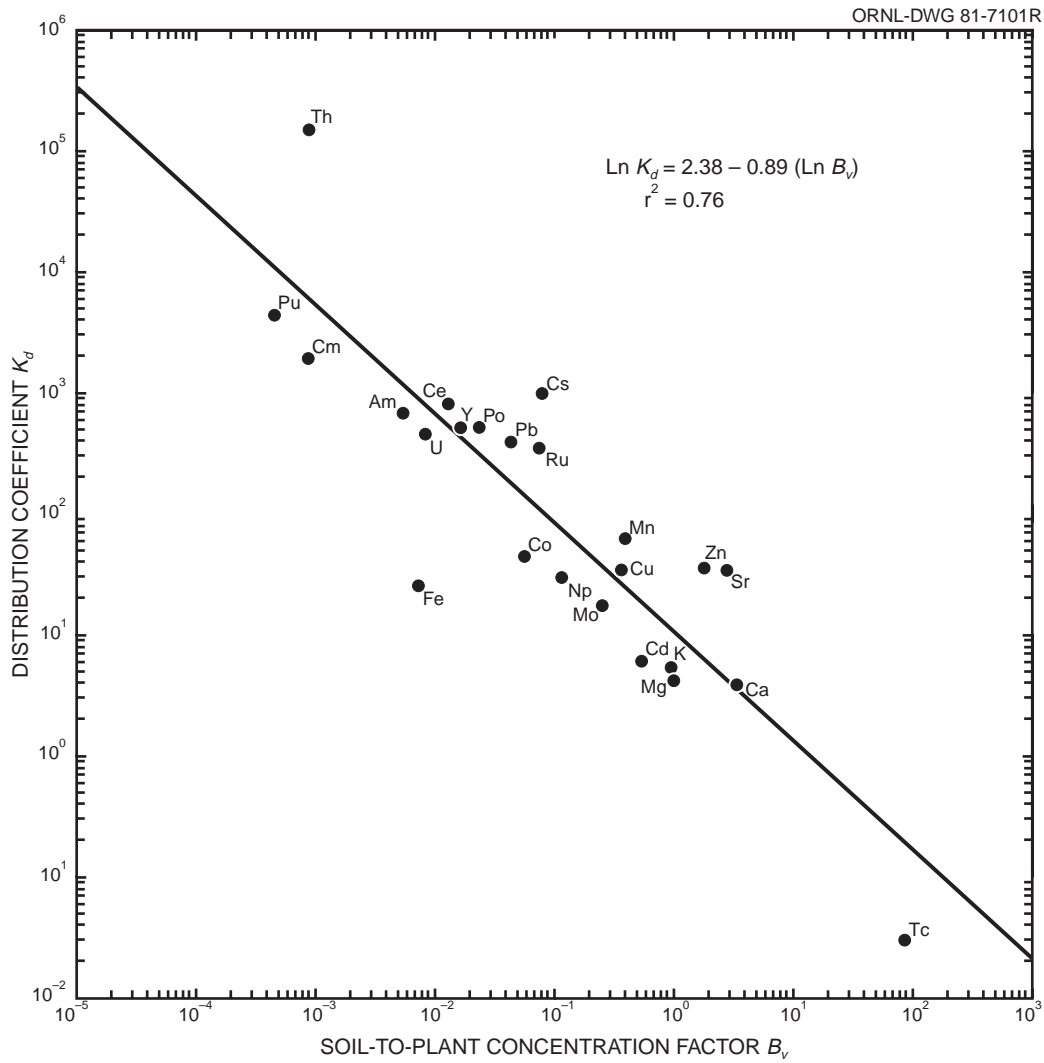


Figure 2.34. Correlation between  $B_v$ , and  $K_d$  based on geometric means of available reference geometric means.