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W.I. Robison, T.F. Hamilton, C.L. Conrado, S. Kehl

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W.L. Robison, T.F. Hamilton, C.L. Conrado, and S. Kehl
Lawrence Livermore National Laboratory
7000 East Avenue, L-642
Livermore, CA 94550-9234
USA

Abstract

Cesium-137 was deposited on Bikini Island at Bikini Atoll in 1954 as a result of nuclear testing and has been transported and cycled in the ecosystem ever since. Atoll soils are of marine origin and are almost pure $CaCO_3$ with high concentrations of organic matter in the top 40 cm. Data from previous experiments with mature fruit trees show very high transfer factors (TF's), [Bq g^{-1} plant/ Bq g^{-1} soil, both in dry weight] into fruits from atoll calcareous soil. These TF's are much higher than reported for continental, silica-based soils. In this report TF's for 5 types of leafy vegetable crops and 2 types of grain crops are provided for use in predictive dose assessments and for comparison with other data from other investigators working with other types of soil in the IAEA CRP "The Classification of Soil Systems on the Basis of Transfer Factors of Radionuclides from Soil to Reference Plants". Transfer factors for plants grown on calcareous soil are again very high relative to clay-containing soils and range from 23 to 39 for grain crops and 21 to 113 for leafy vegetables. Results from these experiments, in this unique, high pH, high organic content, low potassium (K) soil, provide a boundary condition for models relating soil properties to TF.

1. INTRODUCTION

The United States conducted nuclear tests at Bikini Atoll from 1946 through 1958. Bikini, the main residence island, was contaminated by fallout on March 1, 1954 as a result of test Bravo that was part of Operation Castle series of tests. Other atolls down wind of Bikini were also contaminated. About 90% of currently estimated dose for people returning to live on Bikini is from ^{137}Cs accumulated by plants from soil (1; 2). Detailed radioecology studies have been conducted for 25 y to determine general transport of ^{137}Cs at the atoll and uptake of ^{137}Cs from coral soil to major tree fruits, coconut (Coco nucifera), breadfruit (Actocarpus altilis), Pandanus (Pandanus spp.), papaya (Carica papaya), and banana (Musa spp.) that are prevalent in the local diet and contribute much of the estimated dose to returning residents (3; 4; 5).

Transfer factors (TF's) developed from these studies indicate a much higher uptake in plants of ^{137}Cs from coral soil (2; 6) than reported for continental, silica-based soils (7). Presented in this report are TF's for ^{137}Cs for a variety of leafy vegetables and grains to supplement predictive dose assessments for atoll living and supply comparative data for IAEA CRP, "The Classification of Soil Systems on the Basis of Transfer Factors of Radionuclides from Soil to Reference Plants" that includes data from investigators from 14 countries working with many different types of soil.

2. ATOLL SOIL

Atoll soils are of marine origin and consist primarily of calcium carbonate, some magnesium carbonate, organic carbon, nitrogen, and phosphorus (P) mixed in new surfaces or older buried surface layers. There are essentially no clay minerals. Organic matter (OM) is very low in new soil or sand at the edge of an island but ranges between 50- and 150-g kg^{-1} (5 to 15%) in the dark surface soils in island interiors. Deeper organic layers are found in interior regions of larger islands. The OM concentration is high in the surface but decrease abruptly through a narrow transition zone about 25 to 30 cm deep. Observable organic matter is essentially absent below depths of 40- to 50- cm. Most all roots involved in absorption of nutrients are in the top 40- to 50-cm organic-containing layer.

Phosphorus (P) content of atoll soil ranges from 2- to 6-g kg^{-1} but is quite variable and can be as high as 5- to 15- g kg^{-1} in some areas as a result of past guano deposits from nesting birds. Atoll soil is very low in total K and concentrations range from 0.2- to 0.4-g kg^{-1} (3; 8). Extractable K ranges between 20 and 80 mg kg^{-1} (0 to 30 cm) and 1 to 10 mg kg^{-1} below 30 cm. Sixty to 75% of the extractable K is water-soluble [r^2 = 0.72 to 0.98 in various soils] (Stone and Robison, unpublished data). Potassium concentrations are highest in the 0 to 10 cm layer and originate from sea spray and decaying vegetation. Water-soil slurries pH ranges from 7.3 to as high as 8.8 (3) and cation exchange capacity from 12 to 24 cmoles kg^{-1}. More detail on elemental content of soil in test plots in this study is listed in Table 1.

Because clay minerals are non-existent or present in extremely small amounts and Ca is available in large amounts, relative uptake into plants of ^{137}Cs and ^{90}Sr in atoll soils is reversed from that observed in continental soils. Cesium-137 uptake is high in atoll soils, while ^{90}Sr uptake is very low (3; 6).

3. EXPERIMENTAL DESIGN AND METHODS

The experimental site is located near the middle of Bikini Island in a relatively clear area where the coconut grove is about 30 m from experimental plots. This area is within a region of the island with the highest ^{137}Cs concentrations in soil. A backhoe was used to excavate a 1 m deep trench, near the coconut grove boundary and around the entire plot area, to prevent coconut roots from penetrating the study site. A four-block design was used with 12 individual plots in each block (Figure 1).

Chinese Cabbage (Wong Bak, Brassica pekinensis), sorghum (Sorghum bicolor, cv. Cargill #40), and a hybrid cabbage (KK Cross, Brassica oloeracea var. capitata L.), were initially selected for random planting in each of 24 plots in Blocks 1 and 2 (Figure 2a).

Subsequent to harvest of this first crop, a second crop was planted where corn (Zea Mays, Hawaiian hybrid) replaced sorghum, Amaranth (Amaranth, Tricolor L.), sometimes referred to as Chinese spinach Yin Choi, replaced Wong Bak, and Kai Choi (Brassica juncea L.), sometimes referred to as leaf mustard, replaced KK Cross (Figure 2b). Blocks 3 and 4 were planted with corn (Zea Mays, cv. Silver Queen), Amaranth, and Mizuna (Brassica, campestris L.), all randomized among the 24 plots (Figure 2c) immediately after second planting of Blocks 1 and 2.

Table1. Composition of Bikini Island soil in the test-plot area

Soil depth cm	Block	Plot	pH	EC µs/cm	$CaCO_3$ (%)	Inorg. C (%)	KCl extract NH4-N mg/kg	KCl extract NO3-N mg/kg	Total Cu mg/kg	Total Fe mg/kg	Total K mg/kg	Total Mg g/kg	Total Mn mg/kg	Total Na g/kg	Total P g/kg	Total Zn mg/kg	Exch. Al mg/kg	Exch. Ca mg/kg	Exch. Cd mg/kg	Exch. Co mg/kg	Exch. Cr mg/kg	Exch. Cu mg/kg	Exch. Fe mg/kg	Exch. K mg/kg	Exch. Mg mg/kg	Exch. Mn mg/kg	Exch. Na mg/kg	Exch. Ni mg/kg	Exch. P mg/kg	Exch. Pb mg/kg	Exch. Zn mg/kg
0 to 40	2	C	7.31	292	87.8	10.5	4.99	11.4	4.30	142	607	16.2	69.7	2.66	3.07	80.8	0.86	355	0.053	0.007	0.041	0.360	3.20	14.5	19.9	7.3	13.4	0.037	14.5	0.080	53.3
0 to 40	2	D	7.28	353	89.2	10.7	5.64	8.27	1.90	87.4	469	14.6	36.0	2.81	2.58	263	0.80	450	0.059	0.007	0.041	0.355	4.00	16.8	41.7	7.0	15.2	0.033	21.7	0.104	84.4
0 to 40	2	E	7.24	325	84.3	10.1	6.58	4.76	1.74	110	402	13.2	9.2	3.03	2.09	14.0	0.93	506	0.059	0.003	0.037	0.212	2.55	18.3	42.7	2.7	17.3	0.042	19.2	0.058	14.1
0 to 40	2	F	7.32	296	87.6	10.5	10.4	10.7	1.34	46.9	392	13.8	7.1	2.52	1.85	13.8	1.0	536	0.079	0.004	0.045	0.167	3.36	21.0	61.8	3.6	29.8	0.033	36.7	0.067	28.0
0 to 40	2	G	7.3	310	86.0	10.3	13.9	13.2	1.52	93.8	363	14.0	6.2	2.65	3.46	8.6	1.3	546	0.148	0.003	0.055	1.315	5.33	22.2	35.7	4.3	18.4	0.030	32.7	0.126	17.7
0 to 40	2	H	7.41	331	84.7	10.2	16.2	16.6	1.25	81.6	354	16.5	21.3	2.90	2.80	228	1.1	441	0.108	0.009	0.052	0.240	5.91	21.7	56.6	10.0	21.0	0.037	34.4	0.115	279
0 to 40	2	I	7.37	316	84.3	10.1	6.05	11.6	2.32	417	481	14.6	45.6	2.84	1.78	56.7	0.84	401	0.047	0.008	0.036	0.304	4.18	17.8	43.6	13.4	19.6	0.044	37.9	0.177	127
0 to 40	2	J	7.28	320	84.7	10.2	4.56	7.60	1.17	90.7	354	12.8	4.5	2.62	2.76	9.2	0.87	442	0.052	0.003	0.046	0.270	2.27	16.9	48.4	2.6	22.3	0.036	50.4	0.126	10.4
0 to 40	2	K	7.34	482	81.8	9.8	11.5	7.91	1.43	63.6	358	14.0	8.8	2.66	5.84	17.1	1.1	519	0.102	0.002	0.047	0.130	4.12	21.1	50.6	3.0	29.4	0.033	32.3	0.138	13.7
0 to 40	2	L	7.31	346	83.1	10.0	15.9	23.4	1.64	53.6	311	11.7	10.3	2.54	3.12	94.6	1.2	543	0.114	0.005	0.050	0.199	5.00	21.1	30.5	5.4	28.6	0.039	25.2	0.124	29.0
0 to 20	1	B	7.38	325	83.9	10.1	14.8	12.8	1.41	33.5	316	13.8	12.7	2.49	5.67	18.6	1.2	580	0.142	0.003	0.049	0.113	6.00	25.4	42.1	5.2	43.0	0.048	45.4	0.072	21.5
0 to 20	1	C	7.44	373	83.0	10.0	19.7	12.6	1.11	28.1	321	13.1	16.7	2.54	4.42	46.4	1.1	532	0.112	0.006	0.261	0.135	5.40	25.0	88.2	10.5	25.4	0.104	74.0	0.070	151
0 to 20	1	E	7.39	324	82.7	9.9	12.7	7.51	0.83	22.4	292	10.9	19.3	2.35	2.91	41.6	1.0	537	0.122	0.006	0.063	0.100	6.76	22.6	83.6	10.6	24.2	0.039	59.2	0.067	120
0 to 20	1	F	7.43	354	85.5	10.3	19.2	10.6	1.03	27.8	297	14.2	17.1	2.49	3.55	47.1	1.1	567	0.140	0.005	0.060	0.110	6.35	26.7	94.2	8.6	26.5	0.037	60.2	0.077	62.3
0 to 20	1	G	7.34	303	84.3	10.1	11.3	17.4	1.03	29.8	297	14.4	16.4	2.71	4.24	24.7	1.2	532	0.151	0.004	0.065	0.142	5.63	22.8	34.1	9.7	24.1	0.040	43.8	0.100	39.8
0 to 20	1	I	7.45	302	84.7	10.2	14.1	8.14	0.981	28.9	295	14.6	37.4	2.54	4.20	38.8	1.1	557	0.108	0.005	0.046	0.117	4.34	23.7	110	10.5	24.8	0.026	121	0.068	60.3
0 to 20	1	K	7.4	308	78.1	9.4	13.6	8.56	0.820	23.3	304	13.6	9.8	2.64	3.50	12.9	1.1	551	0.118	0.003	0.053	0.109	4.97	25.0	96.6	6.8	25.7	0.027	65.9	0.059	18.4
0 to 20	1	L	7.44	342	83.5	10.0	22.8	9.87	1.12	31.6	306	11.5	16.6	2.35	3.84	44.4	1.0	557	0.152	0.005	0.061	0.139	5.68	25.2	85.2	7.8	22.2	0.035	44.7	0.066	31.5
0 to 20	2	A	7.35	313	86.6	10.4	19.1	10.2	2.76	41.1	256	12.2	56.3	2.43	4.05	75.6	1.3	535	0.168	0.006	0.067	0.153	6.54	22.3	45.3	12.5	16.7	0.030	48.8	0.057	82.7
0 to 20	2	D	7.37	329	87.1	10.5	9.79	13.3	1.20	24.2	220	9.9	14.5	2.30	2.86	41.7	0.95	496	0.088	0.006	0.071	0.088	4.71	19.5	72.1	6.6	17.5	0.041	46.0	0.045	40.0
0 to 20	2	E	7.35	306	85.1	10.2	12.4	11.7	0.962	27.7	157	9.4	17.7	2.37	2.76	39.6	1.2	512	0.132	0.008	0.068	0.134	5.87	21.3	59.5	10.4	19.1	0.036	43.1	0.085	56.0
0 to 20	2	F	7.33	402	78.6	9.4	21.4	17.0	1.31	34.8	180	11.4	16.4	2.14	3.60	20.6	1.3	605	0.201	0.006	0.079	0.246	5.73	31.2	96.2	8.6	46.1	0.040	86.2	0.104	21.4
0 to 20	2	G	7.35	356	77.7	9.3	18.2	13.1	1.32	33.5	148	11.7	16.1	2.26	3.55	28.1	1.5	583	0.199	0.006	0.088	0.211	7.31	22.4	39.9	9.1	17.3	0.033	52.4	0.123	40.5
0 to 20	2	H	7.36	358	82.1	9.9	14.2	10.4	0.890	26.1	141	10.5	15.2	2.23	2.96	30.6	1.2	546	0.151	0.007	0.103	0.150	5.43	23.9	60.2	10.5	32.6	0.040	47.9	0.096	46.7
0 to 20	2	J	7.32	392	82.6	9.9	12.2	18.2	1.16	21.9	141	10.7	11.8	2.17	3.89	23.9	1.2	546	0.136	0.005	0.111	0.117	3.87	24.1	83.9	7.1	33.4	0.033	97.5	0.137	19.9
0 to 20	2	K	7.33	433	81.8	9.8	19.6	9.54	1.15	30.7	145	10.5	25.4	2.51	3.88	43.0	1.3	547	0.182	0.008	0.095	0.149	6.62	25.9	65.4	10.3	42.7	0.038	60.6	0.090	63.1
0 to 20	4	A	7.2	710	80.4	9.6	7.52	60.7	1.16	28.5	124	9.0	9.6	2.44	3.23	10.6	1.0	530	0.108	0.008	0.155	0.134	3.93	22.4	113	3.4	65.1	0.050	31.5	0.098	10.2
0 to 20	4	B	7.29	519	84.4	10.1	12.2	53.1	1.68	75.6	129	9.3	8.7	2.47	4.42	6.8	1.2	461	0.104	0.011	0.144	0.193	2.19	20.9	60.1	2.9	45.3	0.047	42.2	0.116	2.7
0 to 20	4	C	7.24	583	68.8	8.3	7.75	59.3	3.41	62.6	157	9.7	38.4	2.35	5.02	84.4	0.89	218	0.073	0.020	0.164	0.136	1.37	15.8	31.8	2.9	20.1	0.044	0.3	0.023	0.0
0 to 20	4	D	7.29	614	68.6	8.2	8.84	49.2	2.42	87.2	162	8.7	10.1	2.46	4.30	11.5	1.3	564	0.126	0.009	0.140	0.359	2.25	28.4	91.2	5.3	48.3	0.053	73.6	0.123	5.0
0 to 20	4	F	7.24	632	77.1	9.3	6.83	78.0	1.88	50.9	155	9.0	16.2	2.48	6.45	20.9	2.1	612	0.202	0.005	0.086	0.304	6.95	21.5	77.9	6.9	60.0	0.086	49.6	0.093	14.8
0 to 20	4	G	7.3	423	79.6	9.6	5.64	26.1	1.86	47.8	165	9.3	12.3	2.42	4.54	17.9	0.22	86	0.000	0.000	0.000	0.063	0.00	14.5	21.7	0.0	21.4	0.000	0.2	0.000	0.0
0 to 20	4	H	7.26	717	77.3	9.3	9.01	60.2	1.46	32.7	142	8.2	5.8	2.29	2.88	3.9	2.2	690	0.178	0.008	0.052	0.196	5.21	55.4	134	3.2	82.2	0.056	52.5	0.078	2.2
0 to 20	4	I	7.18	1110	78.1	9.4	8.65	164	1.83	63.1	126	9.1	10.7	2.42	4.27	10.0	2.2	689	0.157	0.003	0.073	0.216	5.71	33.7	125	3.0	82.7	0.056	51.8	0.077	2.2
0 to 20	4	K	7.23	713	74.5	8.9	12.5	84.0	2.12	52.4	154	9.5	13.0	2.45	5.34	10.9	1.6	452	0.142	0.003	0.068	0.194	6.04	24.4	95.6	3.9	67.9	0.049	40.5	0.060	4.8
0 to 20	4	L	7.26	628	79.6	9.5	6.98	64.2	1.80	35.5	128	11.2	8.4	2.53	4.26	10.0	1.3	475	0.143	0.000	0.054	0.142	4.70	54.5	82.7	3.5	70.9	0.023	50.9	0.043	5.3
0 to 20	3	A	7.24	751	80.7	9.7	6.73	113	1.28	24.1	122	9.0	5.4	2.47	2.96	9.0	1.6	447	0.094	0.001	0.054	0.138	4.16	22.3	78.3	2.4	62.4	0.043	46.3	0.049	1.7
0 to 20	3	B	7.26	686	80.8	9.7	7.38	87.6	1.50	27.7	139	10.7	7.5	2.60	3.81	7.6	1.2	510	0.083	0.005	0.052	0.128	3.82	19.6	77.2	2.4	54.2	0.049	44.9	0.063	4.5
0 to 20	3	D	7.24	683	79.9	9.6	6.78	111	1.63	51.1	129	9.2	8.8	2.28	3.17	5.2	1.8	792	0.097	0.005	0.063	0.217	5.06	22.3	82.2	3.4	60.8	0.051	58.6	0.117	2.4
0 to 20	3	E	7.22	949	78.2	9.4	9.26	117	2.05	33.7	129	7.2	8.7	2.12	4.15	4.9	1.4	301	0.020	0.007	0.038	0.121	4.08	16.4	34.6	3.6	37.5	0.041	0.0	0.000	0.0
0 to 20	3	F	7.28	683	76.2	9.1	11.59	61.3	2.43	45.6	141	7.9	13.3	2.18	5.86	10.1	1.9	603	0.193	0.003	0.077	0.248	8.36	23.4	93.0	5.5	70.6	0.060	42.1	0.135	7.4
0 to 20	3	G	7.28	708	95.6	11.5	5.10	110	1.31	22.3	102	8.5	10.6	2.37	3.63	9.2	1.9	640	0.107	0.004	0.058	0.232	5.81	22.5	90.7	4.7	69.0	0.051	60.5	0.119	10.6
0 to 20	3	I	7.2	613	82.7	9.9	7.62	75.0	1.33	20.1	140	12.3	17.0	2.67	3.89	15.1	1.9	521	0.182	0.003	0.076	0.280	0.95	63.1	85.6	6.9	69.8	0.054	55.9	0.235	14.7
0 to 20	3	J	7.26	615	72.1	8.7	4.40	92.5	2.29	27.5	141	12.2	13.0	2.35	2.78	9.8	3.6	516	0.158	0.004	0.077	0.148	0.47	54.4	104	4.5	70.0	0.045	50.0	0.266	7.3
0 to 20	3	K	7.3	492	88.2	10.6	9.01	119	2.10	44.6	145	9.7	9.5	2.07	4.07	7.1	0.84	189	0.044	0.000	0.021	0.067	2.16	15.3	38.8	1.4	19.7	0.012	15.6	0.012	1.3
0 to 20	3	L	7.3	745	69.6	8.3	12.49	107	2.32	58.6	147	10.0	27.4	2.27	6.28	35.4	0.55	191	0.068	0.000	0.026	0.096	2.72	15.6	29.3	3.1	19.6	0.015	21.3	0.041	7.3
0 to 40	4	D	7.4	653	85.0	10.2	8.29	58.8	1.76	42.7	149	12.7	8.5	2.60	5.49	9.7	1.3	539	0.211	0.000	0.063	0.146	1.50	57.6	171	3.3	77.0	0.015	64.4	0.151	3.3
0 to 40	4	F	7.38	473	100.3	12.0	7.74	45.7	1.06	22.9	109	11.9	5.9	2.68	4.54	15.2	1.4	518	0.181	0.003	0.060	0.113	0.51	52.2	80.8	1.9	67.0	0.034	26.6	0.231	4.5
0 to 40	4	I	7.38	734	82.3	9.9	6.85	101	0.643	17.4	104	12.7	5.8	2.50	2.27	5.6	0.99	527	0.165	0.000	0.055	0.105	0.69	52.9	111	2.9	75.8	0.030	28.5	0.169	3.6
0 to 40	3	D	7.33	533	119.3	14.3	5.79	85.3	0.717	24.1	97.7	13.8	5.2	2.76	2.77	43.0	1.6	598	0.070	0.002	0.054	0.134	3.73	18.8	93.6	2.0	56.8	0.051	34.0	0.110	1.7
0 to 40	3	G	7.34	557	74.9	9.0	5.94	93.2	0.636	26.3	104	11.0	5.1	2.58	1.55	4.1	2.3	544	0.066	0.000	0.042	0.115	3.65	54.1	87.3	2.8	71.8	0.026	39.0	0.050	4.2
0 to 40	3	I	7.25	858	78.2	9.4	7.49	85.9	1.52	45.8	129	10968	8.5	2577	5.29	7.1	2.3	633	0.132	0.000	0.074	0.150	6.51	54.1	80.1	3.9	92.2	0.044	43.9	0.078	2.3

6 soil cores composited

Note: Soils provided in "Un-ball milled" form.

The Hawaiian hybrid corn died in the second planting of blocks 1 and 2 and a third planting of corn (Zea Mays, cv. Silver Queen) was required. The planting and harvesting schedule is shown in Table 2.

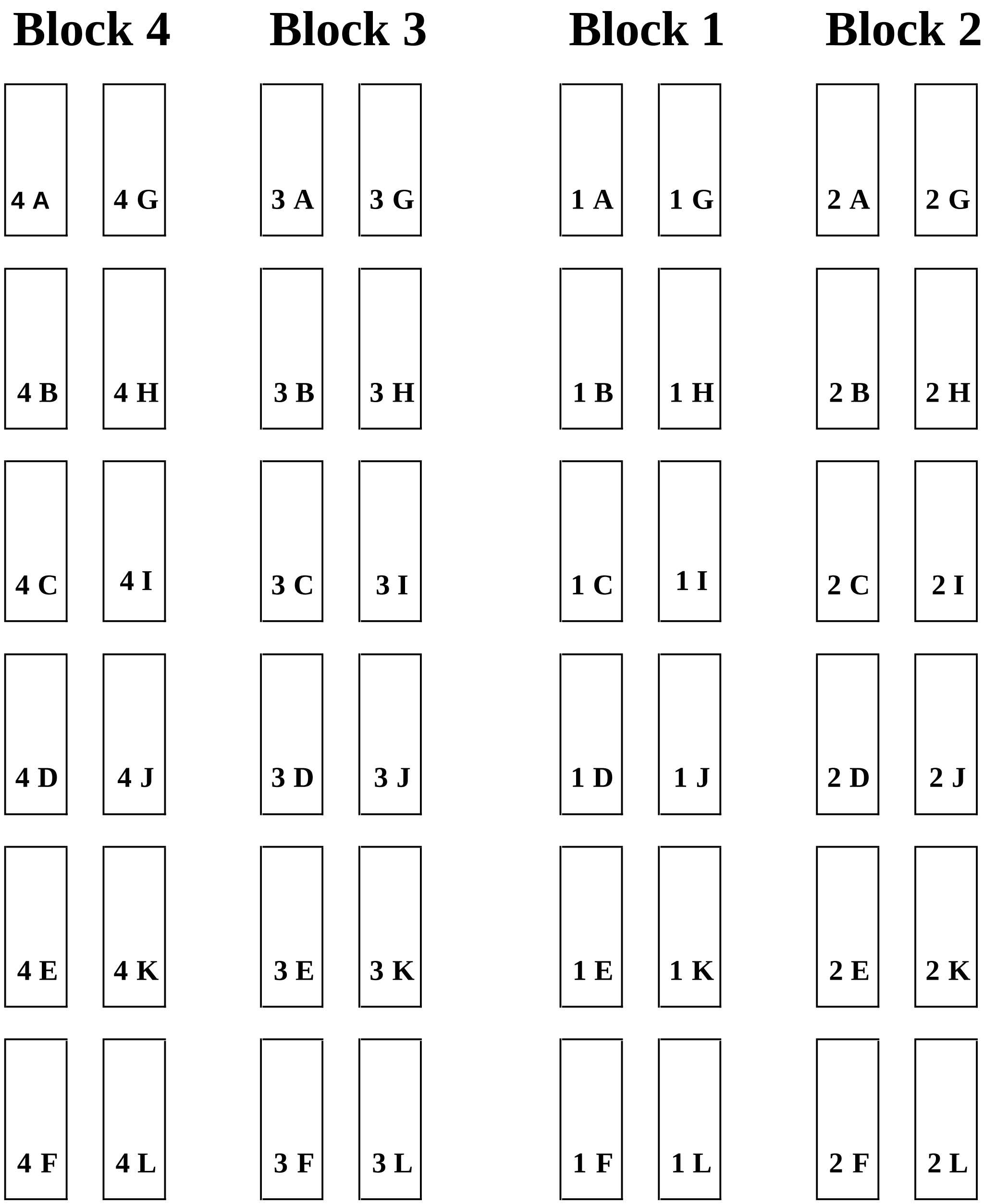


Figure 1. The layout of 4 blocks and 48 plots at Bikini Island.

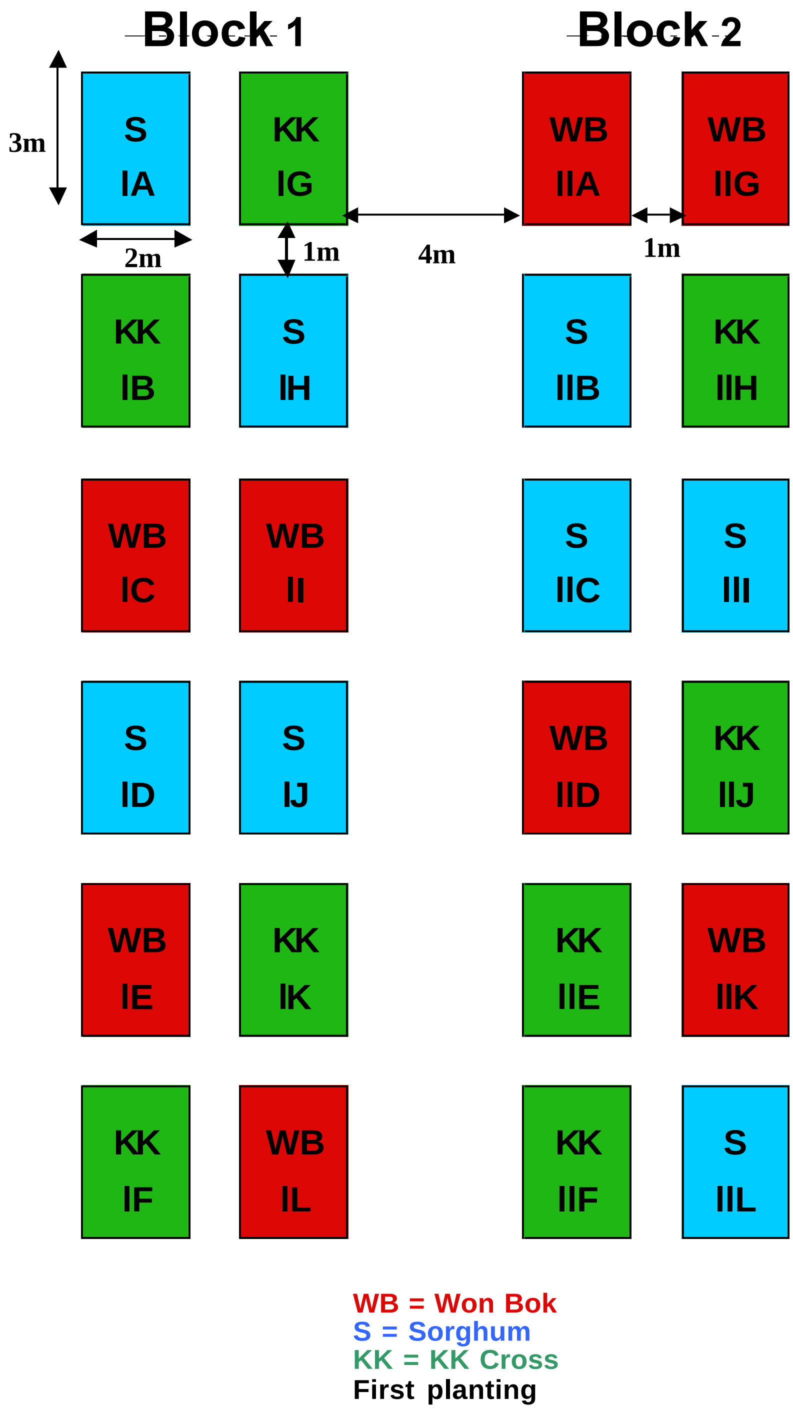
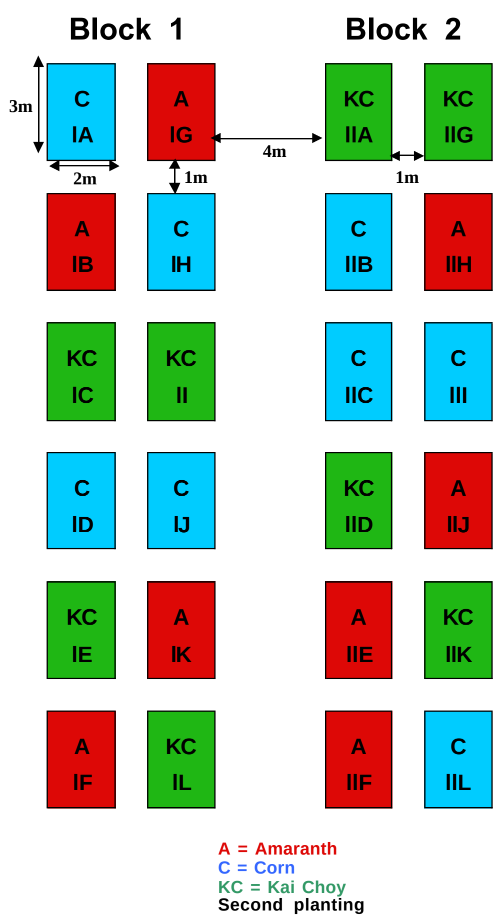


Figure 2a. Distribution of crops in 24 plots in blocks 1 and 2 for the first planting.



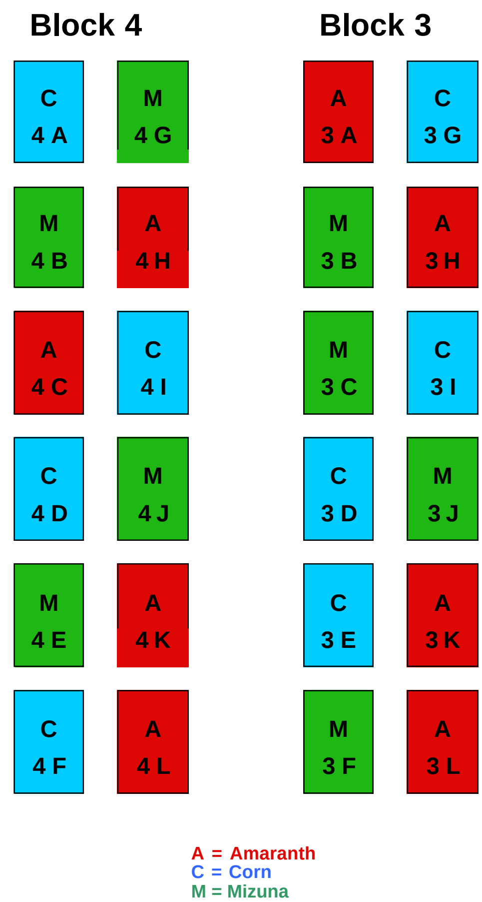


Figure 2b. Distribution of crops in 24 plots in blocks 1 and 2 for the second planting.

Figure 2c. Distribution of crops in 24 plots in blocks 3 and 4.

TABLE 2. PLANTING AND HARVEST SCHEDULE FOR BLOCKS 1, 2, 3, AND 4

Blocks 1 and 2		Blocks 3 and 4	
First planting	**Dates**	**First planting**	**Dates**
Sorghum	5-May-99	Amaranth	6-Nov-99
Won Bok	15-May-99	Corn	5-Nov-99
KK cross	29-May-99	Mizuna	6-Nov-99
First harvest		**First harvest**	
Sorghum	July 22 - July 25, 1999	Amaranth	11-Dec-99
Won Bok	July 22 - July 25, 1999	Corn	22-Jan-00
KK cross	July 22 - July 25, 1999	Mizuna	Feb./March, 2000
Second planting			
Corn(Hawaaian hybrid)	27-Jul-99		
Amaranth	September, 1999		
Kai choy	September, 1999		
Second harvest			
Corn(Hawaaian hybrid)	all died		
Amaranth	November,1999		
Kai choy	November,1999		
Third planting			
Corn(Silver Queen)	4-Nov-99		
Third harvest			
Corn(Silver Queen)	January, 2000		

Nitrogen (N), P, and trace minerals (T M) were placed in the furrow at the time of planting. Plants were watered if rainfall was inadequate for good plant growth and N and T M were applied as required for quality growth and productivity. The mature crops produced from initial planting of Blocks 1 and 2, along with the mature staff, are shown in Figure 3.

Figure 3. Staff members collecting samples from the first harvest of blocks 1 and 2.

Four soil profiles were collected in the 6 m space between blocks 1 and 2 and blocks 3 and 4 - specifically between plots 3 G and I A, 3 I and 1 C, 3 J and 1 E, and 3 L and 1 F. The increments were: 0 to 5cm, 5 to 10 cm, 10 to 15 cm, 15 to 25 cm, 25 to 40 cm, and 40 to 60 cm. In addition, six 0- to 20- cm punch-tube core soil samples were collected from each plot that contained leafy vegetables. Two samples were taken at each end of a plot, 50 cm in from the end and 65 cm in from both sides of the plot. The other 2 samples were taken at the plot center 65 cm from the sides. The root zone of the leafy vegetables was within the top 20-cm. of soil. Six 0 -to 40- cm punch-tube core samples were taken as described above in all plots containing sorghum or corn. Corn and sorghum have a rooting zone to about 40 cm.

Sorghum seed and corn ears were harvested, double bagged in plastic bags, and placed in freezers on island. Sorghum and corn stovers were cut about 8 cm above ground level, double bagged and placed in freezers. All leafy vegetables were cut just above ground level. They were then rinsed a leaf at a time to ensure there was no residual soil on the organic sample and then double bagged and frozen. All samples were shipped in Matson freezer vans to Lawrence Livermore National Laboratory (LLNL).

At LLNL the vegetation samples were dried by lyophilization to constant weight, ground to fine consistency in a Waring blender, and canned for gamma spectrometry analysis. All soil samples were sifted through a 2 mm screen to remove large pieces of coral that have little ^{137}Cs activity or impact on ^{137}Cs uptake from soil by plants. They were then oven dried at low temperature, ball-milled to a homogeneous powder, and canned for gamma analysis. All samples were packed into steel cans 231 cm^3 in volume for gamma analysis using 20 high-resolution, intrinsic, solid-state, germanium detectors.

4. RESULTS

Distribution of ^{137}Cs in soil between Blocks 2 and 3 after some 25 years of transport and redistribution is shown in Figure 4.

The cumulative distribution is shown in Figure 5. Distribution of ^{137}Cs in the experimental plots is exponential to a depth of about 30 to 40 cm. At depths below about 40 cm, where organic content of soil is very low or non-existent, ^{137}Cs concentration is very low and forms an exponential distribution with a different slope. In island interior locations the organic layer can extend to 40- to 50- cm depth. In such cases ^{137}Cs distribution is a single exponential to 40- to 50-cm. More than 90 % of ^{137}Cs activity in the test plots is contained in the top 30 cm of soil. The ^{137}Cs concentration for either 0- to 20-cm depth or 0- to 40–cm depth for each of the plots is listed in Table 3.

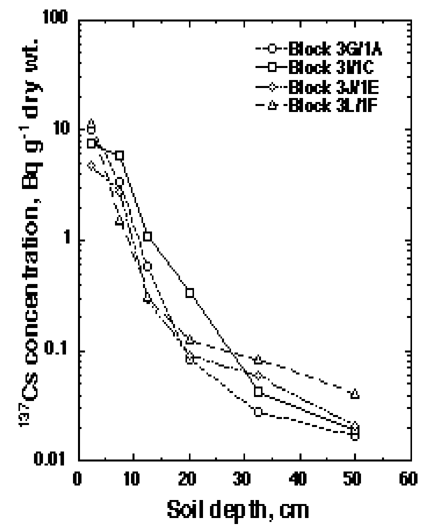


Figure 4. The distribution of ^{137}Cs to a depth of 50 cm in soil in the test area.

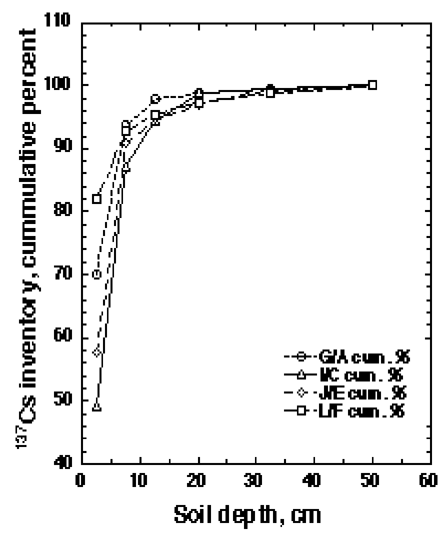


Figure 5. The cumulative distribution of ^{137}Cs to 50 cm depth in soil in the study area.

Table 3. Cs-137 CONCENTRATION FOR 0-20 cm AND 0-40 cm IN PLOTS IN ALL BLOCKS.

^{137}Cs concentration in the root zone of crops					^{137}Cs concentration in the root zone of crops				
Block No.	**Plot No.**	**Bq g^{-1} dry 0 to 40 cm**	**Bq g^{-1} dry w 0 to 20 cm**	**Ratio 0-20/0-40**	**Block No.**	**Plot No.**	**Bq g^{-1} dry 0 to 40 cm**	**Bq g^{-1} dry 0 to 20 cm**	**Ratio 0-20/0-40**
1	A	0.85			3	A		1.1	
1	B	0.68	1.4	2.1	3	B		0.86	
1	C	1.1	2.6	2.3	3	C		0.64	
1	D	1.3			3	D	0.47	0.98	2.1
1	E	0.59	1.1	1.9	3	E	0.49	1.5	3.1
1	F	1.04	2	1.9	3	F		1.4	
1	G	0.47	1.1	2.3	3	G	0.5	1.1	2.3
1	H	0.51			3	H		1	
1	I	1.2	2.7	2.2	3	I	0.96	0.8	0.83
1	J	1.2			3	J		0.92	
1	K	1.1	2.6	2.4	3	K		**3.6**	
1	L	1.2	1.7	1.4	3	L		**2.3**	
2	A	0.46	1.1	2.4	4	A	0.61	1.1	1.9
2	B	0.28			4	B		1.6	
2	C	0.38			4	C		1.8	
2	D	0.45	0.88	2	4	D	1	2.4	2.3
2	E	0.79	1.6	2	4	E		2.2	
2	F	1.1	2.7	2.5	4	F	0.51	0.81	1.6
2	G	0.78	1.4	1.8	4	G		1.1	
2	H	0.95	1.3	1.4	4	H		1.5	
2	I	0.42			4	I	0.7	1.7	2.4
2	J	0.4	1.3	3.3	4	J		2.9	
2	K	0.81	1.8	2.2	4	K		1.6	
2	L	0.81			4	L		1.5	
			Mean	**2.1**				**Mean**	**2.1**
			Stdev	**0.45**				**Stdev**	**0.67**
			No.	**16**				**No.**	**8**
			Stderr	**0.11**				**Stderr**	**0.17**

TF results for each plot, and therefore each planted crop, in blocks 1 and 2, are listed in Table 4 for crops from both the first and second planting. The results from blocks 3 and 4 are listed in Table 5. Transfer factors (Bq g^{-1} dry plant / Bq g^{-1} dry soil) for all the various crops range from about 20 to 110.

Table 4. Cs-137 CNCENTRATION IN PLANTS AND SOIL, AND TF'S FOR EACH PLANT SPECIES IN BLOCKS 1 and 2.

Block	Plot	Plant	^{137}Cs Concentration Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 40 cm Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 20 cm Bq g^{-1} dry wt.	TF	Plant	^{137}Cs Concentration Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 40 cm Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 20 cm Bq g^{-1} dry wt.	TF
1	A	sorghum seed	11	0.85		13	sorghum stover	15	0.85		18
1	D	sorghum seed	24	1.3		18	sorghum stover	50	1.3		38
1	H	sorghum seed	18	0.51		35	sorghum stover	23	0.51		45
1	J	sorghum seed	44	1.2		37	sorghum stover	57	1.2		48
2	B	sorghum seed	16	0.28		57	sorghum stover	14	0.28		50
2	C	sorghum seed	26	0.38		68	sorghum stover	22	0.38		58
2	I	sorghum seed	30	0.42		71	sorghum stover	33	0.42		79
2	L	sorghum seed	8	0.81		10	sorghum stover	13	0.81		16
					Mean	**39**				**Mean**	**44**
					Stdev	**24**				**Stdev**	**21**
					N	**8**				**N**	**8**
					Stderr	**8.6**				**Stderr**	**7.3**
1	1C	Won Bok	198		2.6	76	Kai Choy	41		2.6	16
1	1E	Won Bok	210		1.1	191	Kai Choy	32		1.1	29
1	1I	Won Bok	229		2.7	85	Kai Choy	61		1.7	36
1	1L	Won Bok	178		1.7	105	Kai Choy	37		1.7	22
2	2A	Won Bok	90		1.1	82	Kai Choy	28		1.1	25
2	2D	Won Bok	223		0.88	253	Kai Choy	51		0.88	57
2	2G	Won Bok	66		1.4	47	Kai Choy	24		1.4	17
2	2K	Won Bok	114		1.8	63	Kai Choy	29		1.8	16
					Mean	**113**				**Mean**	**27**
					Stdev	**71**				**Stdev**	**14**
					N	**8**				**N**	**8**
					Stderr	**25**				**Stderr**	**4.9**
1	1B	KK Cross	68		1.4	49	Amaranth	29		1.5	19
1	1F	KK Cross	96		2	48	Amaranth			2	
1	1G	KK Cross	49		1.1	45	Amaranth			1.1	
1	1K	KK Cross	139		2.6	53	Amaranth			2.6	
2	2E	KK Cross	148		1.6	93	Amaranth			1.6	
2	2F	KK Cross	74		2.7	27	Amaranth	41		2.7	15
2	2H	KK Cross	89		1.3	68	Amaranth	29		1.3	22
2	2J	KK Cross	83		1.3	64	Amaranth	35		1.3	27
					Mean	**56**				**Mean**	**21**
					Stdev	**19**				**Stdev**	**5.1**
					N	**8**				**N**	**4**
					Stderr	**6.9**				**Stderr**	**2.5**
1	A	Corn ear	3.7	0.85		4.4	Corn stover	8.6	0.85		10.1
1	D	Corn ear	8.1	1.3		6.2	Corn stover	15	1.3		11.5
1	H	Corn ear	4.5	0.51		8.8	Corn stover	9.7	0.51		19
1	J	Corn ear	50	1.2		42	Corn stover	44	1.2		36.7
2	B	Corn ear		0.28			Corn stover		0.28		
2	C	Corn ear	25	0.38		66	Corn stover	19	0.38		50
2	I	Corn ear	4.6	0.42		11	Corn stover	8.8	0.42		21
2	L	Corn ear	14	0.81		17	Corn stover	10	0.81		12.3
					Mean	**22**				**Mean**	**23**
					Stdev	**23**				**Stdev**	**15**
					N	**7**				**N**	**7**
					Stderr	**8.7**				**Stderr**	**5.7**

Table 5. Cs-137 concentration in plants and soil, and TF's for each plant species in blocks 1 and 2.

Block	Plot	Plant	^{137}Cs Concentration Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 40 cm Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 20 cm Bq g^{-1} dry wt.	TF	Plant	^{137}Cs Concentration Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 40 cm Bq g^{-1} dry wt.	^{137}Cs Concentration 0 to 20 cm Bq g^{-1} dry wt.	TF
3	D	corn ears	13	0.47		27	corn stover	18	0.47		38
3	E	corn ears	7.6	0.49		16	corn stover	12	0.49		25
3	G	corn ears	8.5	0.5		17	corn stover	13	0.5		26
3	I	corn ears	18	0.96		18	corn stover	15	0.96		16
4	A	corn ears	14	0.61		23	corn stover	23	0.61		37
4	D	corn ears	19	1		19	corn stover	24	1		24
4	F	corn ears	12	0.51		24	corn stover	10	0.51		20
4	I	corn ears	8.1	0.7		12	corn stover	14	0.7		20
					Mean	**19**				**Mean**	**26**
					Stdev	**5.1**				**Stdev**	**8**
					N	**8**				**N**	**8**
					Stderr	**1.8**				**Stderr**	**2.8**
3	B	Mizuna	53.9		0.86	63					
3	C	Mizuna	51.6		0.64	81					
3	F	Mizuna	73.1		1.4	52					
3	J	Mizuna	LOST		0.92						
4	B	Mizuna	58.4		1.6	37					
4	E	Mizuna	58.7		2.2	27					
4	G	Mizuna	68.8		1.1	63					
4	J	Mizuna	62.4		2.9	22					
					Mean	**49**					
			103		**Stdev**	**22**					
					N	**7**					
					Stderr	**8.8**					
3	A	Amaranth	27.7		1.1	25					
3	H	Amaranth	18.1		1	18					
3	K	Amaranth	35.8		**3.6**	29					
3	L	Amaranth	52.6		**2.3**	23					
4	C	Amaranth	20.7		1.8	12					
4	H	Amaranth	21.2		1.5	14					
4	K	Amaranth	32		1.6	20					
4	L	Amaranth	37.6		1.5	25					
					Mean	**21**					
					Stdev	**5.9**					
					N	**8**					
					Stderr	**2.4**					

A statistical analysis of difference in means between plots containing the same crop in blocks 1 and 2 and in blocks 3 and 4 was made using the nonparametric Mann-Whitney U test for differences in means. A nonparametric method was used because of small sample size (4 plots of each type of crop per block) for which statistical tests based on normal distributions are inappropriate. Nonparametric methods are more efficient and powerful than parametric methods under such conditions.

Results indicate no statistical difference between crops grown in blocks 1 and 2 or between crops grown in blocks 3 and 4. A comparison of results from combined data in blocks 1 and 2 with the combined data from blocks 3 and 4 for crops common to both again show no statistical difference. The lowest observed probability was 0.11 while most others exceeded 0.34. The statistical summary is listed in Table 6. As a result, data for a specific crop from all plots may be combined in calculating mean TF values. A summary of means (± 1 standard error) for all plots that contained the same crop is given in Table 7.

Table 6.MANN WHITNEY U -TEST PROBABILITIES FOR DIFFERENCE IN MEANS. Block1 vs 2, block 3 vs 4, and blocks1 +2 vs blocks 3 + 4.

Plant	probability Blocks 1 vs 2	probability Blocks 3 vs 4	probability Blocks 1 + 2 vs 3 + 4
Sorghum seed	0.34		
Sorghum stover	0.34		
Corn ears	0.22	0.88	~1
Corn stover	0.4	0.69	0.57
Won Bok	0.49		
Kai Choy	0.98		
Amaranth	~1	0.2	0.53
KK Cross	0.34		
Mizuna		0.11	

Table 7. SUMMARYOF MEAN TF's AND ASSOCIATED STANDARD ERROR FOR EACH TYPE OF PLANT

Plant	TF	Stderr
Sorghum seed	39	8.6
Sorghum stover	44	7.3
Corn ears	23	4.3
Corn stover	27	3.5
Won Bok	113	25
Kai Choy	27	4.9
KK Cross	56	6.9
Amaranth	21	1.6
Mizuna	49	8.8

5. DISCUSSION AND CONCLUSIONS

It is clear that transfer factors for all annual food crops and long-lived tree food crops grown in coral soil are very high relative to those reported for continental silica-based soils. The range in TF for ^{137}Cs in coral soil for fruit trees and annual crops is 0.8 to113 based on this report and reference 6. The range in TF for ^{137}Cs in continental, silica-based soils ranges from 0.004 to 0.5 for fruits and vegetables (7). The low end of the TF range for carbonate soils does not overlap the high end of the range from silica soil. On the other hand, TF's for 90Sr are very low in Ca-rich coral soil [range 0.006 to 0.37] (6) while they are relatively high in silica soils [range 0.02 to 3.0] (7). Thus the ^{137}Cs and ^{90}Sr uptake from coral soil to plants is totally reversed from that observed in silica soils. Unique properties of the carbonate soil, and resulting TF's, provide an upper boundary condition for general models relating soil properties to TF.

There is a significant difference in TF's among various leafy vegetables. Mean value of TF's range from 21 for Amaranth to 113 for Won Bak cabbage with Mizuna, Kai Choi cabbage, and KK Cross cabbage in between. Based on these results it would be imprudent to assign a single TF to a category labeled leafy vegetables unless one is willing to accept such a range within a dose assessment. Also, these results indicate a level of information required for more specific application of TF's to dose assessments. There is not nearly as much difference between the two types of grain crops. Mean TF's for sorghum seed and stover are 39 and 44, respectively and for corn kernels and stover 23 and 27, respectively. There is no statistically significant difference between the TF for sorghum seed and the stover (p=0.51) or between corn ears and the stover (p=0.38). So either part of these grain-producing plants will provide appropriate information.

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University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551