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^{137}Cs Inter-Plant Concentration Ratios Provide a Predictive Tool for Coral Atolls with Distinct Benefits Over Transfer Factors.

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Abstract

Inter-plant concentration ratios (IPCR), [Bq g^{-1} ^{137}Cs in coral atoll tree food-crops / Bq g^{-1} ^{137}Cs in leaves of native plant species whose roots share a common soil volume], can replace transfer factors (TF) to predict ^{137}Cs concentration in tree food-crops in a contaminated area with an aged source term. The IPCR strategy has significant benefits relative to TF strategy for such purposes in the atoll ecosystem. IPCR strategy applied to specific assessments takes advantage of the fact tree roots naturally integrate ^{137}Cs over large volumes of soil. Root absorption of ^{137}Cs replaces large-scale, expensive soil sampling schemes to reduce variability in ^{137}Cs concentration due to inhomogeneous radionuclide distribution. IPCR [drinking-coconut meat (DCM) /*Scaevola* (SCA) and *Tournefortia* (TOU) leaves (native trees growing on all atoll islands)] are log normally distributed (LND) with geometric standard deviation (GSD) = 1.85. TF for DCM from Enewetak, Eneu, Rongelap and Bikini Atolls are LND with GSD's of 3.5, 3.0, 2.7, and 2.1, respectively. TF GSD for Rongelap copra coconut meat is 2.5. IPCR of *Pandanus* fruit to SCA and TOU leaves are LND with GSD = 1.7 while TF GSD is 2.1. Because IPCR variability is much lower than TF variability, relative sampling error of an IPCR field sample mean is up 6- to 10-fold lower than that of a TF sample mean if sample sizes are small (10 to 20). Other IPCR advantages are that plant leaf samples are collected and processed in far less time with much less effort and cost than soil samples.

Keywords. ^{137}Cs; Inter-plant concentration ratio; transfer factors; radionuclide prediction

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1. Introduction

Plant to soil radionuclide transfer factors (TF) [Bq kg^{-1} in plants/Bq kg^{-1} in soil; both in dry weight] have been used for many years to predict concentrations of radionuclides that could be expected in food crops after accidental releases of radionuclides into the environment. TF have been developed from planned greenhouse, pot, and small field experiments where various radionuclides are added to the soil, and from large-scale field experiments in various environments and ecosystems that have been contaminated by nuclear test programs, reactor accidents, or other major accidents. Many reports are available that deal with TF in various types of plants, soil, and ecosystems for both radionuclides and stable elements. Only a few are referenced here as examples (Al-Oudat et al., 2006; Rahman and Voigt, 2004; Frissel, M. J., et al., 2002; Robison et al., 2000; Papastefanou et al., 1999; Sheppard and Eveden, 1990). Various summaries of TF data (and aggregated transfer factors ATF, [Bq kg^{-1} dry weight in food/ Bq m-^{2} dry soil]) have been published over the years (Ng et al., 1982; IAEA, 1994; International Union of Radioecology (IUR) Data Base (2007).

TF are very useful in radiological dose-prediction models to estimate radionuclide concentrations in food crops after a release of radionuclides to the environment with a subsequent estimate of dose to exposed populations. However, in cases where prediction of radionuclide concentration in tree food crops in large contaminated areas with an aged source term are important, the soil sampling required to develop TF values for a specific radionuclide (or stable element) for tree food crops is time consuming and expensive. Moreover, the ratio of the highest to lowest TF values (or the ratio of the 95% confidence limits) can range from a factor of 10 to a factor 100 or more (Tome et al., 2003; Carini, F., 2001; IAEA, 1994; Sheppard and Eveden, 1990; Ng et al., 1982) leading to a large variance. Median or mean values of these wide-ranging data are generally used to predict radionuclide transfer from soil to plants for predictive dose assessments. There is also a large variance associated with TF data from coral atolls in the Marshall Islands (Robison et al., 2000; Robison and Conrado, 1997).

About 90% of the estimated radiation dose to people returning to live on islands affected by U.S. atmospheric nuclear testing at Bikini and Enewetak Atolls results from consumption of locally grown foods that contain ^{137}Cs accumulated from the contaminated soil (Robison et al., 1997). The major intake of ^{137}Cs is mostly from tree crops such as coconut (*Cocos nucifera* L.), *Pandanus* fruit, and breadfruit. Drinking-coconut meat and fluid account for a large part of the dietary in take of ^{137}Cs at the atolls. However, *Pandanus* fruit, breadfruit, and to a lesser extent papaya and banana, also contribute. TF for these and many other plant species have been determined on Bikini and Eneu Islands at Bikini Atoll, eight islands at Enewetak Atoll, and Rongelap Island at Rongelap Atoll where these crops are growing in an environment contaminated with ^{137}Cs and ^{90}Sr. The ratio of high to low values observed in the range of TF data for ^{137}Cs and ^{90}Sr in food crops at Bikini is about a factor of 20 to 30 leading to a high variance in the TF data (Robison et al., 2000; Robison and Conrado, 1997; Robison et al., 1997).

Much of the TF variability results from non-uniform spatial distribution of ^{137}Cs that occurred at time of deposition and subsequent redistribution due to anthropogenic activities on-island since the time of deposition. This is probably the case for most large-scale contaminations after a period of time. Roots from coconut, breadfruit, and *Pandanus* trees extend radially from the trees for 24 m or more. Any reasonable soil sampling scheme that includes both areal and depth distribution of the very large root zone of large fruit trees represents a very small fraction of the contaminated soil occupied by tree roots. This directly leads to a considerable variance in the data because of the very small area sampled when collecting soil relative to the very large area (and volume) of soil occupied by tree roots. Thus, a considerable range of results in TF is unavoidable.

The International Union of Radioecologists (IUR) recently published the results of a web-based questionnaire to identify knowledge gaps on issues related to the protection of the environment (IUR, 2006). A large cross-section of researchers from around globe are agreed that one of the highest research priorities in this field is to develop a better understanding of the transfer of radionuclides in the environment and, more specifically, on the need to understand and estimate uncertainties in radionuclide TF.

Islands at the atolls other than the main residence islands are being considered for use as either potential residence and/or ”agricultural” islands. Currently these islands do not have tree food-crops growing on them and the concentrations of ^{137}Cs and ^{90}Sr in the soil are different from islands such as Bikini, Eneu, or Rongelap where food crops are available and where TF have been determined. In such specific cases it is necessary to predict the concentrations of ^{137}Cs that will occur in tree food-crops to be planted on the islands, and estimate the dose to people consuming the food crops, to help with resettlement and land-use decisions. A strategy that could eliminate the cost and effort associated with the tremendous amount of soil sampling required for TF development on these islands, and at the same time reduce the variance in the resulting product, would be very useful.

Here we present data from the Marshall Islands that demonstrate the value of basing predictions of radionuclide concentration in tree food crops on inter-plant concentration ratios (IPCR) rather than TF between soil and plant. IPCR's are determined for paired trees - one being a tree food-crop the other a native, non-food tree that grow on all the islands at the atolls - whose root systems share a common volume of soil and radionuclide source for the majority of their roots. IPCR strategy applied to specific assessments takes advantage of the fact tree roots naturally integrate ^{137}Cs over large volumes of soil. Root absorption of ^{137}Cs replaces large-scale, expensive soil sampling schemes to reduce variability in ^{137}Cs concentration due to inhomogeneous distribution of radionuclides. The IPCR methodology is not designed to replace TF in large–scale predictive models that usually begin with deposition data (Bq m^{-2}, etc.). They would not work for such an application.

All but a few of the pairs of trees in this study were separated by distances of merely 1 or 2 meters; there were only a few paired trees separated by as much 3 to 4 meters. We have traced the roots from specific trees to determine their radial distance from the trees (24 m or more) and have observed other tree roots from the nearby-neighbor trees in the same volume of soil (coconut roots, and *Scaevola* and *Torunefortia* roots, are readily identified). So by far, most of the absorbing roots of near-neighbor trees are in a common volume of soil and radionuclide pool. The roots systems are massive and the small portion of the roots of one tree that might be outside a common volume of soil is of no consequence.

The IPCR is defined as the ratio of ^{137}Cs concentration in the fruit of a food plant species (coconut, *Pandanus*, etc.) divided by the ^{137}Cs concentration in the leaves of the paired native plant species.

2. Methods

2.1 Sample collection, preparation, and analysis

Thousands of coconut trees, planted on 8-m grid spacing, are growing on islands at Bikini, Enewetak, and Rongelap atolls. Drinking-coconut meat (coconuts at a young stage of development that contain fluid that is drunk and a meat the consistency of gelatin that is eaten) was obtained from coconut trees as one of the food crops because it is an important part of the local-food diet and contributes significantly to the radiation dose people receive from eating locally grown foods. The older copra stage of the coconut development where the meat is a white and firm is also used for flavoring in cooking, or occasionally consumed directly, but to a much lesser extent than the drinking stage.

Pandanus fruit was selected as a second food item because it is common in the diet at the atolls. *Pandanus* trees grow wild and are randomly distributed around the islands. Some have been planted in defined areas around the island. Large, ripe fruit from these trees were collected for processing and analysis.

Native trees that grow on all islands at all atolls in the Marshall Islands, and whose root systems are of similar radial scale and depth as coconut and *Pandanus* tree roots, include *Tournefortia argentea (*also known as *Argusia* and *Messerschmidia)* and *Scaevola taccada*. Actively growing leaves (no senescent leaves) were collected from these trees for comparison with drinking-coconut meat and *Pandanus* fruit. The number of paired trees found at the atolls for use in analysis of inter-plant correlation coefficients is: 17 pairs of drinking-coconut and *Scaevola* trees and 18 pairs of drinking-coconut and *Tournefortia* trees were located on Bikini Island; 24 pairs of drinking-coconut and *Scaevola* trees and 17 pairs of drinking-coconut and *Tournefortia* trees were located on islands at Enewetak Atoll; 9 pairs of drinking-coconut and *Scaevoala* trees and 6 pairs drinking-coconut and *Tournefortia* trees were located on two islands at Rongelap Atoll; 3 pairs of *Pandanus* and *Scaevola* trees were found on Bikini Island, and 3 pairs on Rongelap Atoll; 3 pairs of *Pandanus* and *Tournefortia* were found on Bikini Island and 1 pair on Aej Island at Enewetak Atoll.

Drinking-coconut meat, copra meat, and Pandanus fruit, and associated soil samples, have been collected over many years to develop TF data for hundreds of coconut trees at Bikini, Enewetak, and Rongelap Atolls and for a number of Pandanus trees at the atolls.

Leaf and drinking-coconut meat samples collected on the islands were double bagged in the field, placed in large Matson freezer vans shortly after collection, and shipped frozen to Lawrence Livermore National Laboratory (LLNL). At LLNL vegetation samples were lyophilized to constant dry weight, ground to fine consistency, and packed in steel cans (233 cm^3) for analysis of ^{137}Cs by gamma spectroscopy. Soil profile samples were collected in increments of 0-5 cm, 5-10 cm, 10-15 cm, 15-25 cm, and 25-40 cm from the sidewalls of trenches dug radially from the tree trunk for several meters. This provided a method for collecting uncontaminated samples to determine the distribution of ^{137}Cs with depth (significant for purposes of remediation) as well as the necessary data for TF calculations. Most all atoll tree roots involved in water and electrolyte absorption are in the top 40 cm of soil that contains nearly all organic material in the soil profile. There is very little organic matter from 40 cm to the water table at about 3 to 3.5 m depth. Soil samples were oven dried at LLNL at low temperature to constant weight, then ball-milled to a fine powder and packed in steel cans (233 cm^3) for analysis by gamma spectroscopy. The gamma spectroscopy facility (GSF) consists of 22 high-resolution, solid-state, intrinsic germanium detectors and the spectra are analyzed using the Canberra GENIE system. Details on calibration of the detectors were reported previously (Brunk, 1995; Hamilton et al., 2000).

A set of samples submitted to the GSF included blind-duplicate samples and standard samples each totaling 10% of the number of submitted samples. Results for the standards had to be within 10% of the accepted standard value or re-analysis was required. Similarly, the blind-duplicate samples had to be within 10% of each other or else this triggered a re-analysis. No re-analyses were required in these data.

2.2 Statistical Analyses

Measured coconut:leaf ^{137}Cs-concentration ratios $R_{k,j,i}$ involving two leaf types ($k = 1,2$, denoting *Scaevola* and *Tournefortia*, respectively) each compared to corresponding samples of drinking-coconut meat from nearby coconuts gathered on eight different islands ($j = 1,\ldots,8$), were analyzed for homogeneity. They were characterized statistically using $n_{k,j}$ to denote the number of ratios measured for each leaf-type and island. Island-specific sets of ln(ratio) values were (if $n_{k,j} > 3$) each assessed for consistency with a normal distribution using the Shapiro-Wilk test (Royston, 1992). Sample geometric mean (GM) and geometric standard deviation (GSD) values were calculated for each of these data sets, and Student's t-test (Kendall and Stuart, 1979) was done on the hypothesis that ln(ratio) = 0 (which is equivalent to the hypothesis that GM = 1). For each test (Shapiro-Wilk and Student’s t) the corresponding leaf-type and island-specific set of up to 8 p-values reported in columns 3 or 6 of Table 1 was adjusted for multiple independent tests using Hommel’s Bonferroni-type adjustment algorithm (Wright, 1992). Each combined set of values, $\ln(R_{k,j,i})|k$ for each leaf type, was assessed for homogeneity using the nonparametric Kruskal-Wallis test (Lehman and D'Abrera, 1975). In any set(s) of leaf-specific values $\ln(R_{k,j,i})$ determined to be significantly nonhomogeneous, the small subset values of island-specific ratios with a GM found to differ significantly from 1 were adjusted by a common factor of 1/GM determined for that data set (i.e., were normalized to have a GM = 1). This procedure maximized the statistical power of variance estimation based on all available data despite the fact that *Tournefortia* ratios from Bikini and Rongelap were found to be < 1 (see Section 4). Resulting data were combined into a single set of raw (and, as just described, potentially adjusted) ratios R_i for all islands and both leaf types, where $i = 1,\ldots,n$, and $n = \sum_{k=1}^{2}\sum_{j=1}^{8} n_{k,j}$.

The combined set of $\ln(R_i)$ values was assessed for normality by Shapiro-Wilk test and homogeneity by Kruskal-Wallis test, as measured by corresponding unadjusted p-values. Finally, parameters of a lognormal distribution fit to n combined measures R_i were then estimated by least-squares linear regression of the sorted log-ratios $\ln(R_{(i)})$ against corresponding standard-normal (Van der Waerden) z-scores, $z_i = \mathrm{F}^{-1}(i/[n+1])$ for $i = 1,\ldots,n$, where F^{-1} is the inverse cumulative standard normal distribution function. Consistency of the empirical distribution of combined ln(ratio) values with an estimated normal distribution was also assessed using modified Kolmogorov-Smirnov (D), Camer-von-Mises (W^2) and Watson (U^2) statistics (Stephens,1970).

The following procedure was used to compare variability among combined, adjusted sets of coconut:leaf (IPCR) ratios, R, to that among coconut:soil (TF) ratios measured on four different islands (Eneu, Enewetak, Rongelap and Bikini). A lognormal fit was obtained as described above for each island-specific set of ln(TF) values, after verifying consistency with the lognormal assumption. Some TF data for Eneu and Rongelap involved subsets of trees for which multiple measures were obtained over a period of time. Specifically, an average (±1 SD) of 6 ± 4 measures/tree was made on each of 90 trees among 125 trees studied on Eneu, and 3.4 ± 1.5 measures/tree were made on each of 59 trees among 232 trees studied on Rongelap. Corresponding lognormal fits were obtained by weighted least-squares linear regression of $\ln(S_{(i)})$ on z_i (as explained above), using tree-specific sample numbers as weights. Finally, fitted regression slopes for island-specific TF data were compared to the fitted slope of the combined, adjusted R-data by analysis of covariance (ANOCOVAR) for linear regression (Selvin, 1995), and corresponding variances were also compared using Bartlett's test (Snedecor and Cochran, 1989).

Monte Carlo methods were used to compare the expected magnitudes of relative error (defined as the upper 2-tail 95% confidence limit, divided by the expected value) of sampled mean values of R vs. TF data. To do this, sample means were obtained for each of 5,000 simulated sets of k values, each sampled from a specified (R- or TF-specific) lognormal distribution, with k fixed at 10, 20 or 60.

All calculations were done using *Mathematica* 5.2® and related software (Wolfram, 1999; Bogen, 2002).

4. Results

Coconut:leaf ratios of ^{137}Cs concentration measured from *Scaevola* and *Tournefortia* leaves and corresponding nearby-coconut samples gathered at eight different Marshall Islands locations are summarized in Table 1. *Scaevola* ratios obtained from each island are consistent with null hypotheses concerning log-normality and GM = 1 (Table 1), and combined log-ratio values for this leaf type from all islands are statistically homogeneous ($p = 0.12$). *Tournefortia* ratios from each island are consistent with null hypotheses concerning log-normality and GM = 1, except with respect to the latter hypothesis for ratios from Bikini ($p_{adj} = 2.0\times10^{-6}$) and possibly those from Rongelap ($p_{adj} = 0.096$, $p_{non\text{-}adj} = 0.016$) (Table 1). The combined log-ratio values for *Tournefortia* from all islands are inconsistent with a null homogeneity hypothesis ($p = 0.0071$), but are quite consistent with this hypothesis when ratios from Bikini and Rongelap were dropped ($p = 0.20$). After the sets of *Tournefortia* ratios from Bikini and from Rongelap were each scaled by factors 1/GM using the respective island-specific GM estimates listed in Table 1, and the ratios for both leaf types from all islands were then combined, the 109 combined ratios became consistent with null hypotheses concerning log-normality ($p = 0.79$), GM = 1 (0.24), and ln ratio homogeneity ($p = 0.10$) (Table 1).

The lognormal model fit to the combined data (Figure 1) corresponds to the following estimated values (and corresponding 95% confidence limits) for the geometric mean and geometric standard deviation: GM = 0.935 (0.928, 0.942), GSD = 1.85 (1.83, 1.86). The empirical distribution of combined ln ratio values was found to be consistent with the corresponding estimated normal distribution based on modified Kolmogorov-Smirnov (D), Camer-von-Mises (W^2) and Watson (U^2) statistics ($p > 0.15$, all three tests). Note that for the purpose of estimating confidence limits on GM, the t-test done on combined ln ratio values was not as powerful statistically as the linear regression done involving these values. Consequently, while the t-test did not detect statistically significant deviation from GM = 1, the regression did.

Results obtained imply a GSD of approximately 1.85 for the combined ratios of ^{137}Cs in drinking-coconut meat to that in *Scaevola* and *Tournefortia* leaves, with *Scaevola* leaves yielding ratios found to have GM values consistent across all islands, and *Tournefortia* leaves somewhat less so.

TF data obtained on Eneu, Enewetak, Rongelap, and Bikini are shown with corresponding lognormal fits (light lines) in Figure 2, and for comparison the combined *R*-data and fit (bold line) from Figure 1. Each island-specific set of ln(TF) data was found to be approximately normally distributed ($p > 0.01$, by Shapiro-Wilk test). The island-specific log-TF slopes (corresponding to GSD values ranging from 2.1 to 3.5) and corresponding variances all differ significantly from one another ($p < 10^{-10}$, by ANOCOVAR), and all are significantly larger ($p < 10^{-10}$, by ANOCOVAR and by Bartlett's test) than that obtained based on the combined, adjusted multi-island *R*-data (corresponding to GSD = 1.85). Consequently, TF data gathered from all four islands indicate that TF variability is greater or substantially greater (on all island except Bikini) than leaf-based measures of ^{137}Cs uptake into drinking coconut meat.

IPCR of *Pandanus* fruit (another contributor of ^{137}Cs in the diet) *to Scaevola and Tournefortia* leaves (10 data points) also are log-normally distributed with a GM of 4.1 and GSD of 1.7. Corresponding TF data for nine *Pandanus* trees has a GM of 1.5 and GSD of 2.1, again indicating considerably greater variability using the TF rather than leaf-based approach to estimating dietary ^{137}Cs based on radioecology data.

5. Discussion

Results obtained in this study indicate substantial statistical homogeneity of leaf:coconut ratios of ^{137}Cs concentration measured from *Scaevola* and *Tournefortia* leaves and corresponding nearby-coconut samples gathered from three atolls and eight different islands in the Marshall islands. Only *Tournefortia* ratios obtained from Bikini and Rongelap appeared to be clearly, or possibly, sampled from populations with a GM significantly <1. After adjusting for this source of bias, the combined set of 109 measures involving two leaf types from a total of eight islands were found to be statistically homogeneous and log-normally distributed with a GM of 0.935 and a GSD of 1.85. By the method of moments (Aitchison and Brown, 1957), it is readily shown that such a lognormal distribution has an expected value of $m = 1.13$.

These findings support the general conclusion that ^{137}Cs concentration C in drinking-coconut meat throughout the Marshall Islands may be estimated reliably by sampling ^{137}Cs concentration S in a sufficient number of *Scaevola or Tournefortia* leaves, and multiplying it by the expected value (m =1.13) from the IPCR data, $C = S$*1.13. Although geographic variability in S is log-normally distributed with a GSD of 1.85, the sample mean of S is an unbiased estimator of the expected value of S, regardless of the number (s) of samples of S taken. However, for small sample size k, substantial statistical uncertainty will be associated with the sample mean of S. For example, relative error of the estimated arithmetic mean of S would be 4.1%, 12%, or 21% for sample sizes of $k = 60$, $k = 20$, or $k = 10$, respectively. In contrast, this relative error would be as high as 68% ($k = 20$) or 210% ($k = 10$) using the TF method on an island like Enewetak (GSD = 3.48) which is a 6- to 10-fold greater relative error using TF as compared the IPCR based approach, if only 10 to 20 samples are taken.

To reduce uncertainty in ^{137}Cs TF for trees requires more and more soil sampling to try to cover the very large area encompassed by the absorbing root zone of large fruit trees. To do this requires an enormous amount of work, time, and expense. In the IPCR strategy the massive roots of the trees do the integrating that one is trying to accomplish with very extensive soil sampling and they do it far better than any reasonable soil-sampling scheme. This is the primary reason that the variance in the IPCR data is much lower than the TF data.

Also, the processes of radionuclide uptake between the plant roots and the soil are very complex due to soil properties such as pH, clay content, CEC, K and Ca concentration, etc. and can greatly affect the magnitude of the TF. Thus, a slight difference in soil composition from one location to another can be a problem when TF developed in one location is applied in another location. As a result, a lot of time-consuming work is required to collect soil samples in every new location. The IPCR strategy does not deal with those issues in any direct way. That of course is the benefit of the strategy – it simply reflects the end result of all those complex processes. Roots of the two different types of trees are looking at the same soil. Even though the detailed process of ^{137}Cs (or any other radionuclide) uptake by the roots may differ in some ways between the two species of trees, it is reflected in the ratio of the ^{137}Cs concentration in the food and non-food trees. The ^{137}Cs concentration in each of the trees reflects the end result of whatever processes lead to the uptake into the plants and would be consistent relative to each other no matter the location.

Other advantages of the IPCR strategy are that it is much less time consuming, less effort, and less costly to generate the required data compared with soil sampling required to develop TF. Leaf samples are vastly easier and far quicker to collect than soil samples. Moreover, weight of leaf samples required is but a tiny fraction of the weight of required soil so they are much easier to handle and transportation costs are greatly reduced. Finally, because processing of leaf samples for submission to the analytical laboratories is simpler and faster than for soil, data are more rapidly attained.

Annual and integral dose estimates for people consuming tree food- crops (coconuts and *Pandanus* fruit) that contain ^{137}Cs can be made for a specific island based on a sampling and analysis of ^{137}Cs in *Scaevola* and/or *Tournefortia* leaves from that island. Observed variance in the IPCR data for ^{137}Cs concentration in both drinking coconuts and *Pandanus* fruit presented in this paper can be used to generate the uncertainty and individual variability in annual and integral doses (Robison et al., 1997; Bogen et al., 1997). This proposed application of IPCR data, particularly for small sample sizes, would result in dose estimates with less uncertainty than what would be generated using TF data.

As with TF data, the IPCR cannot be used immediately after deposition but only after a reasonable steady state has been developed between the radionuclide deposition on the soil and uptake by plants of the radionuclide in question. But that is the case when interest is in the longer-term consequences of a major deposition of radionuclides in the environment such as in the Marshall Islands. Also, the IPCR's are not designed to replace TF in large–scale predictive models that usually begin with deposition data (Bq m^{-2}, etc.). They would not work for such an application.

As a result of the Chernobyl accident (and other sources of contamination) there may be contaminated areas around the world where the IPCR method could be used to more easily develop predictions of radionuclide concentrations in tree food-crops in alternate locations rather than develop TF data. The only requirement is that roots of the native, non-food tree have the same general distribution of roots, aerally and with depth, as the food trees. The advantages are significant if the situation is appropriate.

6. Conclusions

Inter-plant concentration ratios (IPCR) can be used to predict radionuclide concentrations in tree food crops from one location to another at coral atolls. The massive roots of the trees do the integrating in the IPCR strategy that one is trying to accomplish with very extensive soil sampling in the TF method in order to reduce uncertainty (in IPCR and TF) due to the inhomogeneous distribution of radionuclides in the soil. Also, any difference in uptake of ^{137}Cs due to soil composition from one location to another is reflected in a similar way in both the food trees and the native trees. Variance in IPCR data is one half to one third that for corresponding transfer factor (TF) data developed in the same atoll ecosystem. Other IPCR method advantages are that leaf samples can be collected and processed in far less time with much less effort and cost than soil samples. Thus, final data can be obtained more efficiently and rapidly. This approach has important implications in providing guidance for resettlement and/or use of former test sites in the northern Marshall Islands and may be applicable to other radioactively contaminated regions or accident sites where tree food-crops are important in the diet.

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Figure 1. Lognormal fit to 109 combined measures of coconut:leaf ^{137}Cs ratio (ICPR) for *Scaevola* and *Tournefortia* leaves and corresponding nearby-coconut samples, gathered on eight different islands. Data were adjusted for suspected downward bias in 18 and 3 *Tournefortia* ratios sampled on Bikini and Rongelap, respectively. The sorted ratios $R_{(i)}$ and corresponding standard-normal scores, $z_i = F^{-1}(i/[n+1])$ for $i = 1,\ldots,n$ where F^{-1} is the inverse cumulative standard normal distribution function, are plotted (open points) together with the linear fit of $\ln(R_{(i)})$ on z_i (line) and corresponding squared coefficient of correlation (R^2). The model-parameter estimates (±1 SE), $m = -0.067 \pm 0.004$ and $s = 0.614 \pm 0.004$, correspond to an estimated geometric mean GM = 0.935 and geometric standard deviation GSD = 1.85, where m and s here denote log(GM) and log(GSD), respectively.

Figure 2. Lognormal fits to island-specific sets of values of coconut:soil ^{137}Cs ratio (TF) measured for *n* different trees on three islands (Eneu, Enewetak and Rongelap), compared to coconut:leaf ^{137}Cs ratio (ICPR) values and corresponding lognormal fit (bold line) obtained for multiple islands (from Figure 1). Corresponding island-specific model-parameter estimates (±1 SE) are: $m = 2.19 \pm 0.013$, $s = 1.25 \pm 0.013$, GSD = 3.48, $R^2 = 0.988$, $n = 125$ (Eneu); $m = 2.10 \pm 0.014$, $s = 1.11 \pm 0.015$, GSD = 3.03, $R^2 = 0.980$, $n = 115$ (Enewetak); and $m = 0.423 \pm 0.006$, $s = 1.01 \pm 0.006$, GSD = 2.73, $R^2 = 0.992$, $n = 232$ (Ronelap). See Figure 1 legend for notation.

Figure 3. Lognormal fits to island-specific sets of values of coconut:soil ^{137}Cs ratio (TF) measured for *n* different trees on Bikini, compared to coconut:leaf ^{137}Cs ratio (ICPR) values and corresponding lognormal fit (bold line) obtained for multiple islands (from Figure 1). Corresponding Bikini-specific model-parameter estimates (±1 SE) are: $m = 2.51 \pm 0.008$, $s = 0.742 \pm 0.008$, GSD = 2.10, $R^2 = 0.987$, $n = 106$ (Bikini). Note that the Bikini TF slope is significantly greater than the multi-island IPCR slope ($F_{1,211} = 190.0$, $p \approx 0$, by ANOCOVAR). See Figure 1 legend for notation.

Table 1. Summary of coconut:leaf (IPCR) ratios of ^{137}Cs concentration measured in the Marshall Islands.

k = Leaf type j = Island		Number of measured ratios, $n_{k,j}$	Normality^{a} of log-ratios, p_{adj}	Geometric mean, GM	Geometric standard deviation, GSD	Likelihood^{a} that GM = 1, p_{adj}
1. Scaevola						
1	Aej	6	0.99	0.899	1.91	0.97
2	Aomen	8	0.90	0.978	2.40	0.97
3	Bijire	8	0.99	1.02	1.79	0.97
4	Bikini	17	0.99	0.429	1.66	0.97
5	Kabelle	4	0.99	0.655	1.25	0.97
6	Lojwa	4	0.96	1.21	1.93	0.97
7	Lujor	6	0.99	0.549	1.71	0.97
8	Rongelap	7	0.99	0.330	1.28	0.97
2. Tournefortia						
1	Aej	5	0.32	0.899	1.91	0.97
2	Aomen	3	—	0.978	2.40	0.97
3	Bijire	8	0.054	1.02	1.79	0.97
4	Bikini	18	0.32	0.429^{b}	1.66	2.0×10^{-6}
5	Kabelle	3	—	0.655	1.25	0.20
6	Lojwa	3	—	1.21	1.93	0.97
7	Lujor	6	0.32	0.549	1.71	0.21
8	Rongelap	3	—	0.330^{b}	1.28	0.096
Both leaf types						
1-8	All	109	0.79	0.935^{b}	1.85	0.24

[a] P-values are listed for the Shapiro-Wilk test for normality and the Student's t- test hypothesis that ln(ratio) = 0, for leaf-type- and island-specific sets of ln(ratio). Each leaf-type and island-specific p-value was adjusted for multiple independent tests involving the same leaf type. Corresponding unadjusted p-values are shown for tests on combined data for both leaf types from all islands.

[b] *Tournefortia* ratios for Bikini and Rongelap were each normalized by the factor 1/GM, where GM is island specific, to adjust for suspected downward bias pertaining to measures from those islands as indicated by low values of p_{adj} from corresponding t-tests described above.

Figure 1

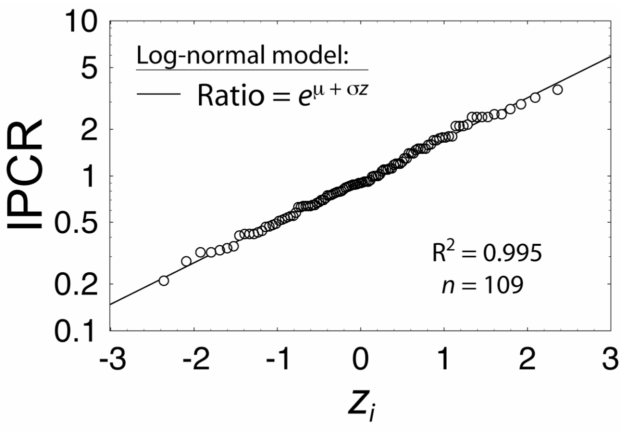

10
5
2
1
0.5
0.2
0.1
IPCR
Log-normal model:
Ratio = $e^{\mu + \sigma z}$
$R^2 = 0.995$
$n = 109$
-3
-2
-1
0
1
2
3
z_i

Figure 2

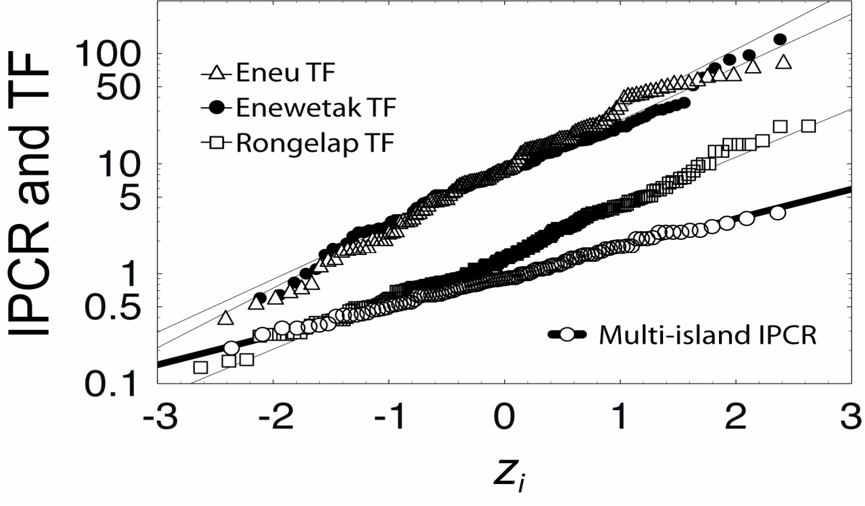
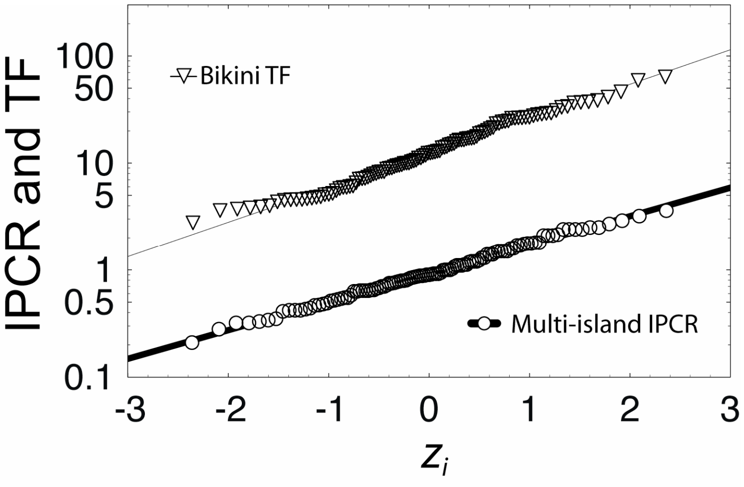

IPCR and TF
100
50
10
5
1
0.5
0.1
-3
-2
-1
0
1
2
3
z_i
Eneu TF
Enewetak TF
Rongelap TF
Multi-island IPCR

Figure 3


IPCR and TF
100
50
10
5
1
0.5
0.1
Bikini TF
Multi-island IPCR
-3
-2
-1
0
1
2
3
z_i