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PATHWAY: A SIMULATION MODEL OF RADIONUCLIDE-TRANSPORT THROUGH AGRICULTURAL FOOD CHAINS[1]

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Abstract.--PATHWAY is a dynamic simulation model of the transport of radionuclides from fallout through an agricultural food chain. PATHWAY simulates the transport of radionuclides both by time dependent, continuous processes such as root uptake and senescence of vegetation, and by discrete events such as tillage of soil and harvest of crops.

INTRODUCTION

This paper describes PATHWAY, a model which was developed to simulate the transport of radionuclides from Nevada Test Site (NTS) fallout through agricultural food chains to man. The reconstruction of estimated radiation doses to residents of the region surrounding the NTS during the 1950s was initiated because of recent concerns about a possible relationship between nuclear fallout exposures and human cancer incidence. The internal radiation doses received by human tissues from ingested radioactivity which contaminated agricultural products can now only be estimated retrospectively through computational procedures because pertinent, direct, contemporary measurements were not made.

The goal of our project is (1) to provide estimates of the time-dependent concentrations of specified radionuclides in the major food products consumed by residents of various localities, ages, and lifestyles, and (2) to provide estimates of the rates of consumption of those foods. These data will then be used in a dosimetric analysis. We believe that the first part of our goal can only be met through the use of a simulation model which is designed specifically for dosimetric evaluation. A high degree of time dependency in the model is essential because (1) acute, time-specific fallout events are to be simulated, (2) the radionuclides that are to be simulated have a wide range of physical half lives, and (3) agricultural practices vary dramatically throughout the year. The model must also be able to accommodate either acute or chronic deposition scenarios and be amenable to validation, sensitivity, and error analyses.

Several models have been developed by other laboratories for the calculation of radionuclide transport through terrestrial food chains (Hoffman et al. 1977, Soldat et al. 1978). However, a review of the available simulation models at the outset of this project revealed none that would meet all of the requirements of the present effort. The majority of these models were developed for regulatory compliance rather than dosimetric evaluations. The development of PATHWAY was undertaken because no existing simulation model could be easily modified to meet these criteria.

PATHWAY is coded in FORTRAN and was constructed with the aid of PREMOD (Kirchner and Vevea, this volume). Thus, the model is designed so that it can be used in either an interactive or a batch mode, and can make full use of the validation, sensitivity, and error analysis routines that are available in the MODAID library associated with PREMOD. The output routines of MODAID that are used in the model provide great flexibility in the production of either tabular or graphical output.

This paper presents the model structure of PATHWAY and the basic concepts underlying the formulations of the processes. The structure and the parameters of the model reflect circumstances and conditions pertinent to selected counties in southern Nevada and Utah which received elevated NTS fallout deposition. Lengthy justification for the use of the many specific parameter values is not provided, as this will be the subject of a future communication. Ongoing efforts to validate the model and to develop error and sensitivity analyses are briefly mentioned.

GENERAL DESCRIPTION

The agro-ecosystem simulated in PATHWAY consists of several individual plots of land called land management units. Each land management unit belongs to one of three subsystems depending on whether it is managed for grazing, for growing food crops, or for growing hay. PATHWAY can simulate simultaneously one or more land management units of each of the three types.

Each land management unit is represented in PATHWAY by a minimum of six state variables, or compartments (fig. 1). These state variables represent the amount of radioactivity ($\mu Ci/m^2$) on the surface of the vegetation, in the tissues of the vegetation, in the surface layer of soil, in the rooting zone of the soil, and in the soil below the rooting zone. The radioactivity in the rooting zone of soil is partitioned into a labile and a non-labile fraction. In addition, each land management unit may have one or more compartments which represent the concentration of

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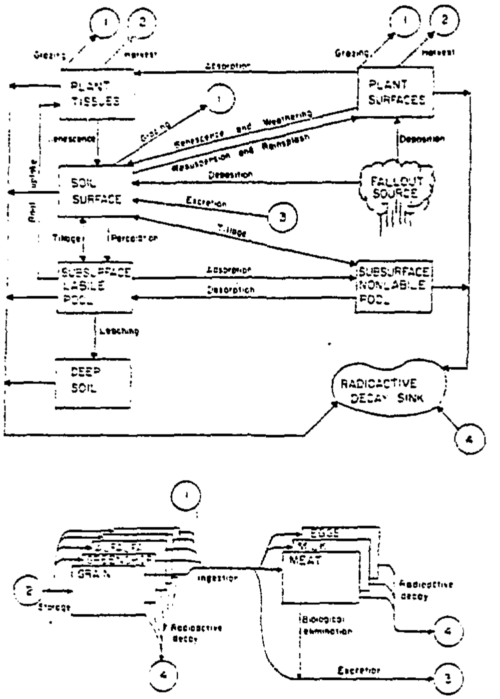

Figure 1.--A generalized flow diagram for one land management unit of the PATHWAY simulation model.

radioactivity in the agricultural products of those units, i.e., the concentration of radioactivity in fruits, vegetables, grains, hay, meat, milk, or eggs.

PATHWAY requires as input three data files: (1) a file of the initial values of the state variables and values for all parameters which are not time dependent, (2) a file of variables which change on a daily basis, and (3) a file of variables which change on a monthly basis during the simulation. The daily input file contains the amount of the radionuclide deposited during each day and for each land management unit, the aboveground biomass of the plants, rates of growth and senescence of the plants, and variables which indicate whether tillage or harvest are to occur. The monthly data file describes the dietary regimen of the livestock on a month to month basis.

Any radionuclide can be simulated in PATHWAY, providing that the appropriate radionuclide-dependent parameters are available. At present, we have assembled parameter values for 20 radionuclides, most of which are the fission products expected to contribute significantly to the radiation dose to humans in a local fallout field. Currently, data files are complete for $^{131\ 133\ 135}I$, $^{136\ 137}Cs$, $^{89\ 90\ 91}Sr$, $^{103\ 106}Ru$, $^{143\ 144}Ce$, ^{97}Zr, ^{99}Mo, ^{140}Ba, ^{132}Te, ^{105}Rh, ^{147}Nd, ^{239}Np, and ^{232}Pu. Parameters for the isotopes of iodine, cesium, strontium, and plutonium are generally based upon the greatest research foundation.

PATHWAY simulates both discrete events and continuous processes which affect the abundance and distribution of radionuclides in the system. The discrete events can occur as frequently as once per day and include the deposition of radionuclides from fallout, tillage of soil, and harvest of crops. The continuous processes include resuspension of contaminated soil, weathering from the surfaces of vegetation, percolation of radionuclides into the soil, adsorption and desorption of radionuclides within the soil, leaching of the contaminant to deep soil layers, uptake of radionuclides by roots, direct foliar absorption, and ingestion and excretion of radionuclides by animals (fig. 1). The continuous processes are represented by first order ordinary differential equations. Some of the coefficients for these equations are time dependent. The system of differential equations are solved numerically using a Runge-Kutta algorithm of order four.

DISCRETE EVENTS

The amount ($\mu Ci/m^2$) of the radionuclide which is deposited each day is read from the daily input file. The partitioning of the fallout between the surface of the soil and the surfaces of vegetation depends upon the aboveground biomass of the vegetation. The proportion of the fallout allocated to the surface of the vegetation, P_d, is given by

$$P_d = 1 - e^{-\alpha B}$$

where,

B = biomass, dry kg/m
α = a constant, m^2/kg (Chamberlain 1970).

α depends upon particle size of the fallout and has a value of about 2.8 for gases and submicron particles such as are represented in worldwide fallout (Hoffman and Baes 1979). However, direct measurements for herbaceous vegetation in areas 80 to 260 miles downwind from the Nevada Test Site indicate that 0.38 is a more realistic value for α for the 5-250 μm fallout particles depositing in Nevada and Utah from explosions on the NTS (Romney et al. 1963, Lindberg et al. 1959).

Tillage of soil redistributes radioactivity between the soil surface (0-0.1 cm) and the subsurface soil of the plow layer (0.1-25 cm). The importance of tillage in determining the concentration of radioactivity in food products is dependent upon the relative timing between the deposition and tillage events. Tillage events soon after the deposition of fallout would reduce the concentration of radioactivity in the surface layer of soil, and thus reduce the importance of resuspension and rain splash as mechanisms by which radioactivity can be transferred to food products. On the other hand, this scenario would lead to increased potential for root uptake. Tillage is simulated by redistributing the total of the inventories in the soil surface and the 0.1-25 cm soil layer in proportion to the relative masses of soil in each layer. Assuming bulk densities of 1.0 and 1.46 g/cm^3 for the surface and subsurface soil, respectively (Lyon, Buckman, and Brady 1952), the surface and subsurface soil receive 0.0027 and 0.9973 of the total radioactivity, respectively.

The effect of a harvest of a food or hay crop is simulated by removing a proportion of the total inventory of radioactivity on the surface and in the tissues of the vegetation. The proportion of radioactivity removed is equal to the proportion of the biomass which is removed during the harvest. Harvest of a crop is initiated by a variable which is read from the daily input file. The biomass of the crop on that day represents the amount of vegetation remaining after the harvest of the crop. Thus, the amount of biomass removed is equal to the difference between the standing crop on the day of the harvest and the standing crop of the previous day.

The concentration of radioactivity (μCi/g) in the harvested vegetation is calculated as the sum of the tissue and surface compartments divided by the biomass of the vegetation and this quantity is assigned to a storage compartment. Only the processes of radioactive decay or the replacement of stored vegetation by vegetation from another harvest affect the level of radioactivity in the stored products. PATHWAY simulates the storage of food crops somewhat differently than the storage of hay crops. On the one hand, there is only one storage compartment for each food crop that is simulated. Thus, this food storage compartment always contains the level of radioactivity remaining in the vegetation from the most recent harvest. On the other hand, there are twelve storage compartments for each land management unit assigned to growing hay. Up to six harvests per year can be stored and these are stored for up to two years. The individual cuttings of hay are stored separately to accomodate diets for grazers which specify both the number of the cutting of the hay and whether that hay came from the previous or the current year.

CONTINUOUS PROCESSES

Radioactive particles in the surface layer of soil can be displaced into the airstream by the action of wind or other mechanical disturbance and these resuspended particles may subsequently deposit on the surfaces of vegetation. Resuspension of radioactive particles is dependent upon such variables as wind speed, soil texture, soil moisture, plant cover, foliage characteristics, and the particle size distribution of the aerosol. Most published models for resuspension calculate the concentration of resuspended radioactivity in the air ($\mu Ci/m^3$) from the product of the density of radioactivity on the surface of the soil ($\mu Ci/m^2$) and a resuspension factor, R. R is determined empirically from the ratio of the air concentration and surface density under steady state conditions, and has units of m^{-1}. Measured values of R which have been tabulated by Stewart (1967) range from about 10^{-11} to 10^{-3} m^{-1}. Anspaugh et al. (1975) have suggested that a reasonable value of R is 10^{-4} because the few measured values which exceed 10^{-4} are associated with artificial disturbances.

Only a fraction of the resuspended radioactivity is deposited on the surface of vegetation. The rate of deposition of resuspended particles is usually estimated by the product of the concentration in air and a deposition velocity, V. The deposition velocity, which has units of m/day, depends upon most of the non-edaphic variables which affect R. V usually is determined empirically. Slade (1968) summarized the results of several experiments in which estimates of V range from 173 to 3197 m/day.

PATHWAY estimates the rate of transfer of radioactivity from the soil to the surface of vegetation directly, i.e., without explicitly calculating a concentration of radioactivity in the air. This rate of transfer is calaculated as the product of R, V, and the density of radioactivity in the surface layer of soil.

Anspaugh et al. (1975) reviewed the literature on resuspension of radioactive contaminants and noted that the concentration in the air over contaminated soil declines with time. This decline is due primarily to a reduction in the fraction of the total soil inventory that is available for resuspension rather than to a loss of radionuclide from the area. An unspecified "weathering" process has been postulated which reduces the erodibility of the contaminant with time (Olafson and Larson 1961, Stewart 1967, Larsen et al. 1966). Langham (1969, 1972) and Kathren (1968) formulated predictive models of resuspension in which the resuspension factor declined exponentially with half times of 35 and 45 days, respectively. Although these models adequately predicted the decline in resuspension for the first few weeks after a deposition event, they greatly underestimated the measured amount of resuspension of plutonium observed in an area seventeen years after the area was contaminated (Anspaugh et al. 1975). Anspaugh et al. (1975) derived another model for the rate of decline of the resuspension factor which better fit the data for long-lived radionuclides.

In contrast to Langham (1969, 1972), Kathren (1968) and Anspaugh et al. (1975), we have assumed that the resuspension factor is constant through time. We have instead modeled a decline in the amount of contaminant available for resuspension due to percolation of the radioactivity from the surface layer of soil to deeper soil layers. Percolation is modeled as a first order rate process with a rate constant of 1.98×10^{-2} day^{-1}, which corresponds to a half time of 35 days.

The impact of raindrops on the surface of soil can also elevate contaminated particles and deposit them onto foliage surfaces. Although rainsplash is in reality a discrete event which occurs only during rainfall, we have assumed that rainsplash can be represented sufficiently well as a linear, first order continuous process. We have derived a value of 8.6×10^{-4} day^{-1} for the rate constant representing rainsplash from the results of experiments conducted by Dreicer (1981).

Weathering consists of processes that transport radioactivity from the surfaces of vegetation to the surface of the soil. Weathering is usually described in the literature as a first order rate process. Rainfall events have little or no effect upon the rate of weathering (Chamberlain 1970). The rate of weathering seems to be most dependent upon whether the radioactivity is in the form of a particulate or a gas. Miller and Hoffman (1979) summarized from many sources the rates of weathering of radioactivity from grasses and other vegetation. These data show half times that range from 8.7 to 28 days for particulates and from 6.5 to 13 days for gaseous radioiodine.

Radionuclides which percolate from the surface layer of soil enter a layer which corresponds to the rooting zone. We assume in PATHWAY that the majority of active roots occur in the soil at depths between 0.1 and 25 cm, and that radionuclides in this subsurface layer of soil can occur as either labile or nonlabile forms. The labile fraction can be taken up by roots or transported to deeper soil layers. The nonlabile fraction represents the portion of the inventory which has been adsorbed to soil particles, particularly clays, and therefore is relatively immobile. Adsorbed radionuclides can re-enter the labile pool through the process of desorption. Adsorption and desorption are represented in PATHWAY as first order rate equations. The coefficients of these equations are highly dependent upon the chemical nature of the radionuclide.

Leaching is the process by which radionuclides of the labile pool in the rooting zone of soil are transported to deeper soil layers and is simulated in PATHWAY as a first order rate process. Although leaching occurs only at a very low rate (Shreckhise 1980), leaching can effectively isolate long lived radionuclides from transport through food chains. Thus, the soil of the deep layers acts as a sink for radionuclides.

Radionuclides can enter plant tissues via two major pathways, root uptake and absorption. Direct foliar absorption of radioactivity is probably much more important than root uptake as a pathway into tissues soon after a deposition event. However, root uptake can become more important as the deposits on the surfaces of the plants undergo weathering and as percolation occurs. Although translocation of radionuclides within the plant tissues is not explicitly simulated, we have assumed that radionuclides taken up by the roots are translocated to the aboveground tissues and that translocation in the reverse direction does not occur.

Absorption is the process by which radionuclides deposited on the aboveground surfaces of vegetation enter the plant tissues. The rate of absorption depends upon characteristics of the foliage and the chemistry of the radionuclide. Absorption is simulated using a first order rate equation. We have assumed that radionuclides which have been absorbed cannot be removed by weathering or washing and that the transfer of radionuclides from the tissues to the surfaces of plants is negligible (Olson 1965).

Only radionuclides in the labile pool of the subsurface soil layer are subject to uptake by roots. The rate of uptake is equal to the product of the concentration of the labile radionuclide, L, the rate of growth of the plants, G, and a radionuclide specific concentration factor determined from the literature, C_f, i.e.,

$$\frac{dT}{dt} = L \cdot C_f \cdot G \quad ,$$

where,

T = plant tissue inventory, $\mu Ci/m^2$
t = time.

The concentration of the radionuclide in soil is calculated by assuming that the inventory of the radionuclide in the labile pool is uniformly distributed throughout the subsurface layer, and that the density of soil in this layer is $1.46 \times 10\ g/m^3$ (Lyon et al. 1952). Although the rate of root uptake is dependent upon the element, edaphic factors, and plant specific factors, we have assumed that the soils in all land management units are similar with regard to root uptake and that differences between species of plants are negligible. Thus, the value of the rate constant used in PATHWAY is dependent only upon the element.

The rate of growth of the plants in each land management unit is read from the daily data file. The daily data file is produced by PLANTS, a model which simulates the growth of plants using an algorithm similar to that for logistic growth, but which includes the effects of temperature and light on the rate of growth of new tissue and a term which represents senescence. The growth rate of plants, G, is given by

$$G = f_d \cdot f_t \cdot R_g \cdot (B_{eq} - B)/B_{eq}$$

where,

R_g = the maximum instantaneous rate of growth of the plants
B = the current biomass
B_{eq} = the steady-state level of B
f_d and f_t = functions for the effect of light and temperature on the growth rate, respectively.

The terms f_d and f_t are restricted to the range of 0 to 1. The value of f_d is equal to the ratio of integrated light intensity on day d and the maximum value of that integral during the growing season (d=168). The temperature function causes the rate of growth to increase with temperature until an optimum temperature is reached, and to decline thereafter. The temperature function for alfalfa is taken from Holt et al. (1975). The temperature function for pasture grass and food crops is similar to that for alfalfa, but the optimum temperature is 30°C rather than 35°C.

As plants senesce, a portion of their aboveground biomass becomes deposited on the surface of the soil as litter. To calculate the flow of radionuclide from plants to the surface of the soil during senescence, we assume that the radionuclide is uniformly distributed in the tissues and on the surfaces of the plants. Thus, the rate of flow from plants to soil is equal to the rate of senescence of the biomass times the sum of the concentrations in the tissues and on the surfaces of the plants.

The rates of senescence of the plants in each land management unit, which are read from the daily input file, are also produced by the simulation model for plant growth. Senescence is assumed to be negligible until after July 31. The rate of senescence, S, is given by

$$S = \begin{cases} 0 & ; \text{month} \le 7 \\ R_s \cdot (B - B_{min}) & ; \text{month} > 7 \end{cases}$$

where,

R_s = a rate constant for senescence
B_{min} = the minimum level of aboveground biomass which persists over the winter months.

The biomass, B, of the plants is simulated by integrating the difference between G and S through time.

The concentrations of radionuclides in meat, milk, and eggs depend upon the rate of ingestion of the radionuclides by the animals. The radionuclides are ingested with the forage or feed of the animals or with soil which is consumed. The animal consumers that are simulated in PATHWAY can be assigned complex diets which include both fresh forage and stored products such as hay and grain (fig. 2). The total rate of ingestion of radionuclides from forage, I_f, is calculated as the sum of the rates of ingestion of each food product, i.e.,

$$I_f = \sum_{i=1}^{n} C_i \, F_i$$

where,

n = the number of food products in the diet of the animals

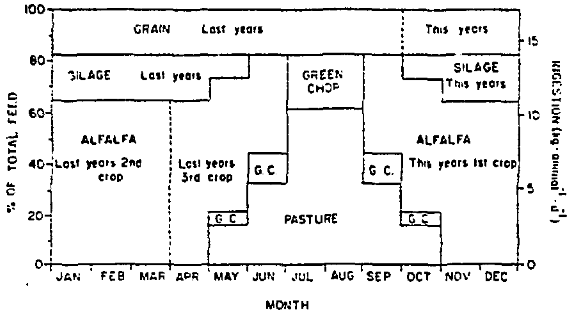

Figure 2.--The standard, or default, diet for dairy cows. The proportions of fresh forage and stored feed in the diet change on a monthly basis.

C_i = the concentration in the i-th food product, µCi/g
F_i = the rate of ingestion of food product i.

The rate of ingestion of radionuclides from soil is calculated as the product of the rate of ingestion of soil (g/day), the density of the radionuclide in the surface layer of soil (g/m^2), and a soil density factor ($0.001\ m^2/g$).

Ingested radioactivity is partitioned between compartments which represent the radioactivity transferred to meat, milk or eggs, or excrement. The assimilation coefficients which determine this partitioning are dependent upon the radionuclide, the species of animal, and whether the radionculide is assimilated from soil or forage. We have assumed that milk and eggs are produced continuously at constant rates. Thus, the concentrations in milk and eggs (µCi/ℓ and µCi/g, respectively) are calculated as the quotients of the rates of transport (intake times the assimilation fraction) of the radionuclides into the animal product compartments and the rates of production of the milk and eggs (ℓ/day and g/day, respectively).

The portion of the ingested radionuclide which is not assimilated into meat, milk, or eggs is assumed to be excreted by the animal onto the surface layer of soil of the land management unit in which it resides. The animal continuously excretes some fraction of the radionuclide that is contained within its muscle tissues. This biological elimination of radionuclides has been measured in many animals and for several radionuclides, and the process usually appears to be adequately respresented by a first order rate equation. Although radionuclides can be retained in other animal tissues, we have assumed that the radionuclides contained in these tissues are negligible compared to the total inventory. Furthermore, most radionuclides reach steady state levels rapidly, so that the rate of assimilation equals the rate of biological elimination.

The radionuclide inventory in the excrement of all animals in a land management unit is assumed to be evenly distributed in the surface layer of soil of that unit. Because the animals in a land management unit can consume food products harvested from other land management units, ingestion and excretion provide the only pathways by which radionuclides can be transported between land management units.

CALIBRATION AND VALIDATION

We are in the preliminary stages of validating PATHWAY against data from studies that measured the transport of radionuclides from fallout or other sources into agricultural products. One problem encountered in the validation simulations was that some important agricultural data often was not collected during the experimental studies. For instance, data on the biomass of the vegetation in pastures, the rates of milk production, and the diets of the animals were often lacking. Therefore, we have made estimates for the values of such parameters to use when no other data are available.

The diets of livestock can greatly influence the rates of ingestion of radionuclides, and thus the concentrations of radioactivity in meat, milk, or eggs. The standard, or default, diet for dairy cattle (fig. 2) is based upon unpublished data for dairy cows in Utah dairy farms (Robert C. Pendleton, personal communication) and data from Hawthorne et al. (1976). The cattle are also assumed to ingest 500 g/day of soil (Mayland et al. 1975, Healy 1968). The default diet of poultry is based upon data from Hurd (1956), Winter and Funk (1956), Morrison (1948), Singen (1969), and Lush (1952). Hens are assumed to eat 10 g/day of soil and 95 g/day of feed, 95% of which is grain and 5% of which is live vegetation. Range cattle and sheep both are assumed to eat only native vegetation (9200 g/day and 1500 g/day, respectively; Cook 1970) throughout the year, and to ingest 500 g/day and 103 g/day of soil (Field and Purves 1964), respectively.

The parameters of the PLANTS model are calibrated to give realistic values for the biomass of vegetation in pastures, alfalfa fields, range lands, and grain crops through the year. We defined harvest dates and the biomass of alfalfa on those dates by extrapolating from data presented by Hawthorne et al. (1956). Parameters affecting the growth of pasture grass have been calibrated to fit data reported by Allred (1965) for irrigated pastures in Utah. The peak standing crop for these pastures is assumed to be $300\ g/m^2$. The growth and senescence rates for grain are assumed to be the same as those for grass, but the potential peak biomass is assumed to be $700\ g/m^2$ (Whittaker 1970). Range vegetation has parameters similar to those for pastures, but the maximum biomass is 125 g/m^2 (Cook 1970).

For our preliminary validation studies, we separated differences between model predictions and measured values into two categories, scaler errors and non-scaler errors. If model predictions differed from measured values by a more or less constant factor, we considered the model to be exhibiting scaler errors. On the other hand, if the differences between model predictions and measured values was not a constant factor, we considered the simulation to be exhibiting non-scaler errors. Scaler errors in a state variable can arise in PATHWAY from consistent errors in the driving variables (deposition data, plant biomasses, etc.) or from an error in the rate equations for that variable. Non-scaler differences are more likely to be caused by errors in parameter values which affect higher order interactions of the state variable, from a basic flaw in the way in which PATHWAY represents the system, or from a time-dependency of a parameter that is not adequately represented in the model.

In our preliminary validation exercies, we are much more interested in discovering non-scaler errors than scaler errors because the magnitude of the non-scaler errors could become quite large in simulations involving long-lived radionuclides. Furthermore, if non-scaler errors are due to a defect in model structure, then it might be fruitless to try to correct the problem by calibrating parameter values.

Examples of our validation studies are the simulations we performed based upon three different experimental studies. The source of the radionuclides in all three studies was worldwide fallout, the radionuclides were all long-lived and the experimental data were collected over intervals of from 3 to 7 years. Thus, these data are especially useful for identifying non-scaler errors. For these simulations, we selected from the range of published values those that appeared most probable (table 1). Although these parameter values were never adjusted to improve the fit between predicted and observed values, we multiplied the results of our validation simulation by a constant factor in cases where PATHWAY consistently over- or under-predicted the observed values. This re-scaling of the simulated values enables us to better compare the dynamics of the model with the dynamics observed in the field experiments. Thus, we can identify the magnitude of any scaler errors, and better assess whether PATHWAY is subject to non-scaler errors.

The first validation exercise is a simulation of the level of cesium-137 in alfalfa over a period of four years (fig. 3). The data for this experiment were collected by Hawthorne et al. (1976). This exercise is particularly valuable because it is one of the few instances in which the biomass of the vegetation, the rate of deposition of fallout, and the concentration of the radionuclide in an agricultural product were all measured. It is obvious that the model has done an excellent job in simulating the concentrations in the alfalfa.

The second validation exercise is based upon data collected by Pendleton (personal communication) who measured the concentrations of strontium-90 and cesium-137 in milk from dairy farms near Salt Lake City, Utah (figs. 4 and 5). We used the default values for diet, milk production rate, and biomass of the pasture vegetation. Data of the amount of Sr-90 in fallout near Salt Lake City was taken from Health and Safety Laboratory (1977). The rate of deposition of cesium was estimated by multiplying the Sr-90 deposition by 1.75, the average ratio of Cs-137 to Sr-90 in worldwide fallout (Edward P. Hardy, Jr., personal communication).

The simulated values of Cs-137 in milk appear to show reasonable dynamics, but are too low by a factor of 3. Differences between simulated and actual values of certain parameters, such as milk production rates and pasture biomass, could account for this scaler error. On the other hand, the simulated values of Sr-90 in milk appear to be too low by a factor of 5, and show non-scaler errors. Re-scaling the simulated values makes it clear that PATHWAY is underestimating the concentration of Sr-90 in milk during the last 3 years of the simulation. It may be possible to eliminate the non-scaler errors by decreasing the rate of loss of Sr-90 from the surface layer of soil, or by increasing the value of the concentration factor for root uptake.

The third validation exercise is based upon data from Ward and Johnson (1963, 1964, 1965a,b) and Wilson, Ward, and Johnson (1965) for a site near Fort Collins, Colorado (figs. 6 and 7). The rate of deposition of Cs-137 was measured using collection funnels over 3 years of the experiment, and the concentrations of the radionuclide in milk and meat of the dairy cows were measured. We again used all default values for the cows' diets and the other parameters of PATHWAY. In this exercise, the simulated values appear similar to the observed values so that no re-scaling was required. Although only six measurements of the levels of Cs-137 in meat were made, PATHWAY appears to simulate these values well. However, PATHWAY seems to have underpredicted the levels of Cs-137 in milk in 1962, but to have overpredicted the levels in 1963 and 1964. We are analyzing these results in an effort to find the source of these non-scaler errors.

SENSITIVITY AND ERROR ANALYSES

We have recently initiated an analysis of the uncertainty in the predictions of PATHWAY (error analysis) and an analysis of the sensitivity of the state variables to changes in the values of the parameters (sensitivity analysis). These analyses require that distributions representing the uncertainty of each parameter be defined. We are presently developing such distributions from data reported in the literature. We are conducting these analyses using analytical routines from the MODAID (Kirchner and Vevea, this volume) library of software.

The preliminary findings of these analyses show that the lists of parameters to which the state variables are most sensitive depend upon the radionuclide and upon the date of the deposition event. Although the list of parameters is not the same for each state variable, the values of the resuspension factor, R, and the initial deposition constant, α, have significant effects on the values of all of the agricultural products. In addition, our analyses indicate that all of the distributions of the predicted values of the agricultural products can be adequately described as lognormal. These results will be discussed in greater detail in a forthcoming publication.

SUMMARY

PATHWAY simulates the transport of radionuclides from fallout through an agricultural ecosystem. The agro-ecosystem is subdivided into several land management units, each of which is used either for grazing animals, for growing hay, or for growing food crops. The model simulates the transport of radionuclides by both discrete events and continuous, time-dependent processes. The discrete events include tillage of soil, harvest and storage of crops, and deposition of fallout. The continuous processes include the transport of radionuclides due to resuspension, weathering, rain splash, percolation, leaching, adsorption and desorption of radionuclides in the soil, root uptake, foliar absorption, growth and senescence of vegetation, and the ingestion assimilation, and excretion of radionuclides by animals.

We are presently simulating an agroecosystem which produces beef, poultry, lamb, milk, eggs, alfalfa, green chop, grain, and garden vegetables. A typical simulation runs in approximately 38 seconds per year simulated in the Colorado State University Cyber 172 computer. However, we are in the process of devising techniques which will reduce the execution time of the model. Preliminary validation studies indicate that the model dynamics and simulated values of radionuclide concentrations in several agricultural products agree well with measured values when the model is driven with site specific data on deposition from world-wide fallout.

Table 1.--Values for the parameters used in the validation simulations of PATHWAY for strontium-90 and cesium-137. The animals in these simulations were dairy cows.

Parameter	Units	Definition	Value	
			Sr-90	Cs-137
A1		Fraction of radionuclide in forage or feed that goes to meat	0.0099	0.5
A2		Fraction of radionuclide in ingested soil that goes to milk	0.0099	0.5
A3		Fraction of radionuclide in forage or feed that goes to milk	0.0183	0.093
A4		Fraction of radionuclide in ingested soil that goes to milk	0.0183	0.093
A5		Fraction of the total soil inventory that remains in the surface layer of soil after tillage	0.002732	0.002732
A6		Fraction of the total soil inventory that remains in the subsurface layers of soil after tillage	0.9973	0.9973
AD	no./m^2	Density of grazing animals	0.00049	0.00049
ALPHA	m^2/kg	Constant used in the function which defines the fraction of fallout that remains on vegetation of a given biomass	2.8	2.8
CF		Concentration factor for root uptake	0.2	0.01
F1	dry g/day-animal	Rate of consumption of vegetation by grazers	17000	17000
F2	dry g/day-animal	Rate of consumption of soil by grazers	500	500
GMASS	wet g/animal	Mass of meat per animal	180,000	180,000
K1	day^{-1}	Rate constant for rainsplash	0.00086	0.00086
K2	day^{-1}	Rate constant for weathering	0.0495	0.0495
K3	day^{-1}	Rate constant for percolation	0.0198	0.0198
K4	day^{-1}	Rate constant for absorption	0.001	0.0055
K5	day^{-1}	Rate constant for adsorption to soil particles	0	0.0019
K6	day^{-1}	Rate constant for desorption from soil particles	0	0.00021
K7	day^{-1}	Rate constant for leaching	0.000066	0.0000066
KB	day^{-1}	Rate constant for biological elimination	0.0932	0.232
KP	day^{-1}	Rate constant for radioactive decay	0.0000657	0.0000633
PRAP	ℓ/day-animal	Rate of production of milk	13.1	13.1
PROG		Proportion of activity remaining in stored grain after harvest	0.25	0.25
R	m^{-1}	Resuspension factor	0.00001	0.00001
RD	cm	Rooting depth of vegetation	25	25
V	m/day	Deposition velocity	173	173

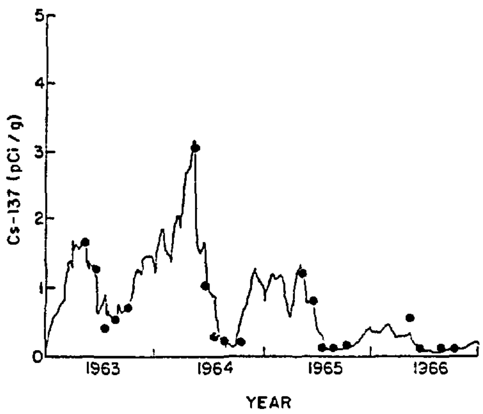

Figure 3.--Simulated (solid line) versus measured (dots) concentrations of cesium-137 in alfalfa from a dairy farm in St. George, Utah.

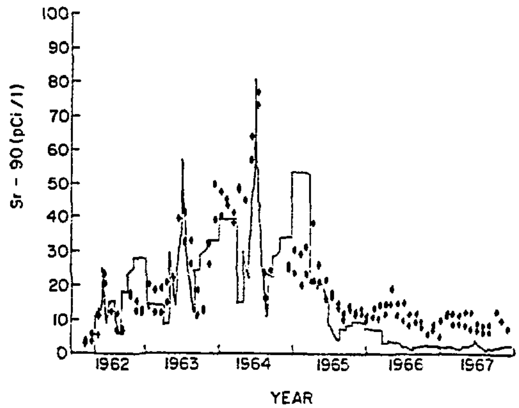

Figure 5.--Simulated (solid line) versus measured (diamonds) concentrations of strontium-90 in milk from dairy farms near Salt Lake City, Utah. After re-scaling the simulated data by multiplying it by a factor of 5, it can be seen that the model is exhibiting non-scaler errors.

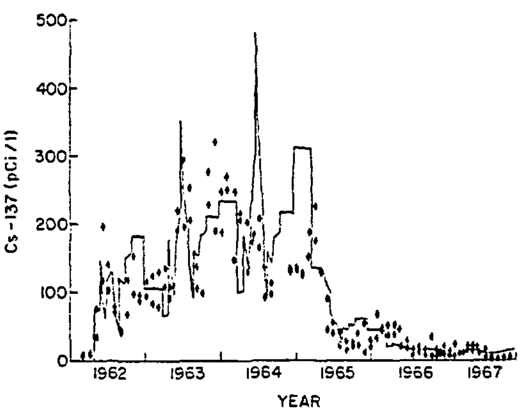

Figure 4.--Simulated (solid line) versus measured (diamonds) concentrations of cesium-137 in milk from dairy farms near Salt Lake City, Utah. The simulated values have been multiplied by a factor of 3 to compare the dynamics of the model to that of the system.

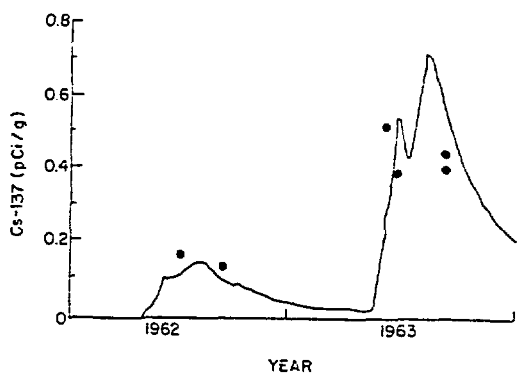

Figure 6.--Simulated (solid line) versus measured (dots) values of the concentration of cesium-137 in meat of dairy cows from Fort Collins, Colorado.

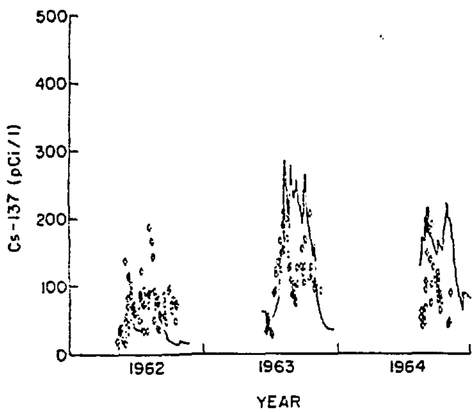

Figure 7.--Simulated (solid line) versus measured (diamonds) values for the concentration of cesium-137 in milk from dairy cows from a farm near Fort Collins, Colorado.

The PATHWAY model currently contributes to evaluations for residents of southern Nevada and Utah. Once we are satisfied with the performance of the model, we plan to expand our data base and, if necessary, make modifications to PATHWAY which will allow it to be used for similar evaluations in other geographic areas and for other sources of radionuclide contaminants.

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